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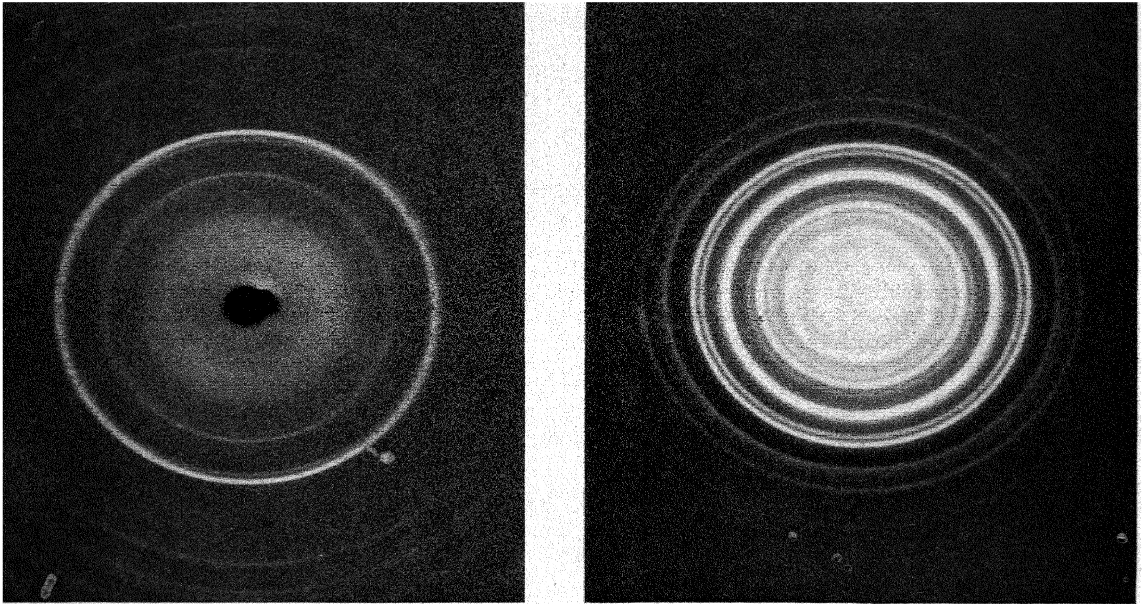

By Courtesy of Dr. Wells *By Courtesy of Prof. G. P. Thomson*

(*a*) (*b*)

Diffraction photographs obtained

(*a*) with X-rays (Quartz) ; (*b*) with Electrons

THE WAVE NATURE OF THE ELECTRON

BY

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PREFACE

The difficulties inherent in the task, here attempted, of setting forth in a book of these dimensions the salient features of one of the most important contributions to scientific thought of all time, are obvious.

The great difficulty in writing on technical matters for a lay public is what to assume as already known. To steer between the Scylla of the obvious and the Charybdis of the specialized requires great care and the dangers of scientific habits of thought are bound to lead one into the error of failing to realize on some occasions that what may seem obvious, is not at all obvious to a reader who has a different background. For such unconscious errors the author can only offer his apologies and express the hope that they are not numerous. There are certain sins both of omission and commission of which he is fully conscious. As regards previous knowledge, it is assumed the reader has read some such book as *The Nature of the Atom* in this series, so that occasional references to atomic structure will not be meaningless.

The title of this book is *The Wave Nature of the Electron*, and, although it is pointed out that the waves under discussion are not peculiar to the electron, but indeed are common to all matter, the general subject being the Wave Nature of Matter, this wave structure was first observed in the case of electrons, and its great scientific importance lay in the fact that it offered, for the first time, a satisfactory means of treating the problem of electron behaviour. The general problem and the experimental evidence for wave structure in the case of matter other than electrons has merely been mentioned. In view of

this statement that the question of electron behaviour has been considered to the exclusion of any discussion on heavier particles, it may be expected that certain other matters might be included which have also been omitted—for example, no mention is made of the Identity Principle or of the Pauli Exclusion Principle. The Identity Principle, which merely states that electrons are undistinguishable, that one cannot speak of *the* electron, but merely of *an* electron, has not been referred to explicitly although it is inherent in much of the discussion. The relevance of the Pauli Exclusion Principle in what purports to be a very general introduction to the study of the behaviour of the electron was not felt to be such as to warrant its inclusion. So far as has been possible, the evidence and results have been made as general as possible. Immediately one passes on to consider the behaviour of electrons under specific circumstances, for example, within an atom, the Pauli Exclusion Principle must be stated and explained. Perhaps one of the most striking successes of the wave theory has been the picture it gives of the phenomenon of Radio-activity, the spontaneous explosion of atomic nuclei. This success, however, with its picture of what is referred to as the " tunnel effect ", is a success of the wave theory of matter and offers brilliant support of the new concepts introduced by such a theory. Its relationship to the Wave Nature of the Electron is no closer than this, and it has been omitted.

It remains to express my thanks to Mr. C. L. Smith and Mr. A. G. Ward for much helpful discussion and criticism.

My thanks are also due to those authors and publishers who have given permission to use plates and blocks for several of the illustrations in the text.

G. K. T. C.

CAMBRIDGE, *July*, *1938*.

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CHAPTER I

Electricity and the Electron

Introduction.

What is an atom? Can we see one? What is electricity? It is a matter of everyday comment that the answers made to simple and obvious questions like these are apt to be long-winded and complicated, if indeed any answer is forthcoming at all. Electricity, as it is commonly understood, is what lights the lamps, heats the stoves, drives the tram cars, and does the million other tasks set it by modern civilization. The power to do all these things lies in the movement of electrons, and in discussing the nature of the electron—the smallest charged body known—we are really answering the question " What is Electricity?"

Electricity and Magnetism.

Under the broad term *electricity*, the popular mind classes a great welter of fact and surmise, and tends by a perfectly understandable process to class under this head all the mechanical mysteries of everyday life. Undoubtedly the most outstanding feature of modern life is its dependence on an electrical slave. Greater experience merely confirms the first impression of the importance of electrical phenomena, for

to-day the structure of matter itself is given an electrical basis.

The history of any science can usually be divided into two stages. There is the early exploratory stage when the fundamental phenomena are discovered, and the science is built up as a self-contained edifice resting on the solid foundation of experimental fact. There comes later the stage when the facts of a science are correlated with those of other sciences, or with science as a whole.

For long the studies of electricity and magnetism were pursued as separate fields of investigation, unrelated both to each other, and to the larger field of mechanics. No doubt the development of the theories of static electricity and of magnetism was greatly facilitated by the formal analogy of some of their properties to the Newtonian law of gravitation, yet the physical relationship of electricity and magnetism only emerged from the study of current electricity, begun about the beginning of last century. Since that time, the importance of these two related sciences has steadily grown, until to-day they may be said to form the corner stones of the scientific universe.

Magnetism.

The study of magnetism began, and for long remained, the study of the properties of the lode-stone, a naturally occurring ore of iron, endowed with directive properties which gave it the name of lode or leading stone. This property of a magnet of setting itself north and south appears to have been known to the Chinese. According to legend a "south-pointing chariot" was constructed as early as 2600 B.C., but it is doubtful if it was applied to any rational purpose such as navigation.

The first comprehensive dissertation on magnetism is the treatise by Gilbert, court physician to Elizabeth and James I, who in 1600 published a book with the title *On the Magnet and Magnetic Bodies and the Great Magnet of the Earth.* Gilbert's

great contribution was the theory that the earth itself is a magnet. The investigation of magnetic properties, based upon the notion of north poles and south poles which exert mutual forces proportional to the product of the pole strengths and falling off as the square of the distance apart, was continued as an isolated subject until the work of Oersted and Ampère linked it up with electricity.

Electrostatics.

The property of amber, on being rubbed, of attracting light bodies was known to the Greeks, indeed the word electron is simply the Greek word for amber. Various substances were found to have similar properties, and about 1733, Dufay observed that two types of electric charge might be generated by this process of rubbing: for instance, sealing-wax, rubbed with cat's fur, attracted any body which glass, rubbed with silk, would repel. The two types of electrification or electric charge were complementary. In fact, as a later experiment of Faraday showed, the process of generating electricity by rubbing generates equal amounts of both kinds, so that if a rod of glass, rubbed with silk, be placed along with the piece of silk on a sensitive detector, the two together show no sign of electrification, though separately they do.

Franklin, about 1750, introduced the very appropriate terms positive and negative to distinguish the two kinds. Franklin was also responsible for the first theory of electricity, viz. that it is an imponderable fluid which permeates all matter, a deficiency corresponding to one type of electrification, and an excess to the other. Some form of fluid theory dominated electrical science for over 100 years; the first evidence which indicated the possibility of an atomic, or particle structure of electricity appeared with Faraday's experiments on the passage of electricity through solutions. Before we discuss these experiments, however, one or two remarks must be made on current electricity.

Current Electricity.

The discovery of current electricity, or, as it was originally called, the galvanic current, was due to the observation (about 1786) of the Italian scientist Galvani that a frog's leg " twitched when an electrical machine was worked near by ". The electrical machine was of the frictional type, familiar to us in our school-days as a means of building up large electrostatic charges. Volta demonstrated later that the source of the electricity lay not in the frog's leg, which in Galvani's experiment merely served as an indicator, but in the contact of two dissimilar metals. The first form of battery, or Volta's pile, as it was called, consisted of discs of copper and zinc placed together, with a piece of flannel soaked in brine between each pair of discs.

It was found by Nicholson and Carlisle in 1800 that the current from such a battery decomposed water, through which it was passed, into hydrogen and oxygen. From these beginnings Faraday built up the *laws of Electrolysis*. It must be observed that at this early stage there was no obvious relationship between the galvanic current and electric charges in motion; indeed, although Volta had asserted that the two were identical, it was a matter that required proof. At a later date it was shown experimentally that the properties of a galvanic current are the same as those of electrostatic charges in motion, that the galvanic current is an electric current, and that the older science is the science of electricity at rest, the newer that of electricity in motion.

Electrolysis.

The facts of electrolysis summed up in Faraday's laws are briefly these.

When an electric current is passed through certain solutions it is found that these solutions are decomposed, one component of the decomposition appearing at the positive electrode, or terminal where the current is said to enter the

solution, the other component being released at the negative electrode. It is found that if, for example, the solution be a compound of hydrogen, a given current of electricity passed for a given time—or in other words a specific quantity of electricity—always releases the same amount of hydrogen irrespective of the nature of the compound. Moreover, if a given quantity of electricity releases 1 gm. of hydrogen, the same quantity of electricity passed through a solution containing silver releases 107·1 gm. of silver.

Now if we accept the atomic theory of the constitution of matter (cf. *The Nature of the Atom* in this series), the ratio of the atomic weight of silver to the atomic weight of hydrogen is 107·1 : 1, so the number of atoms of both elements taking part in the process is the same; and since the same quantity of electricity is involved in the two cases, it follows that the hydrogen atom in the solution is associated with the same quantity of electricity as the silver atom. A similar result holds in general for solutions containing all elements which the chemists call univalent, i.e. those in which one atom forms compounds with, or can replace, 1 atom of hydrogen. Univalent atoms are therefore associated with the same quantity of electricity as hydrogen; those which are bivalent, i.e. form compounds with two atoms of hydrogen, are associated with twice as much electricity. From these experiments we conclude that all univalent atoms in solution carry the same electrical charge. It is true that this does not incontrovertibly demonstrate that electricity has an atomic structure, yet on any other hypothesis the equality of the charges carried by different atoms in the above experiments would be very difficult to explain.

Magnetism and the Electric Current.

We have mentioned that the galvanic current can be identified with electricity in motion. Current electricity is thus linked up with electrostatics. Its relationship with magnetism was discovered by Oersted in 1820. Oersted showed that an

electric current deflected a magnetic needle if the needle were placed parallel to the wire carrying the current; the precise relationship between a magnet and a circuit carrying a current was obtained soon afterwards.

"Oersted stumbled on the principle that a current of electricity had magnetic properties and was virtually equivalent to a magnet. Ampère went further and showed that two wires carrying electric currents could exert a mutual force on each other. Arago and Davy also showed, independently, that a wire carrying a current could magnetize steel and iron, and Ampère pointed out that the amount of deflection of a magnet could be used to measure the strength of the current which caused it." * And if a current moved a magnet, was it not possible that moving a magnet might generate a current? From such an argument Faraday was led to look for the phenomena which led him to his law of induction, the basis of the modern dynamo.

Faraday and Maxwell.

We have seen that the laws of electrolysis appear to indicate that electricity has a particle or atomic structure, yet in themselves they did not suffice (historically) to make this clear. Faraday himself laid stress upon a continuous picture of electrical effects, and held firmly to the idea that an electrified body was a source of electrical stress and strain in the surrounding medium. He was convinced that electrical effects took place by a process of propagation through a medium and not by "action at a distance". Probably the most outstanding success of Faraday's ideas was the demonstration by Maxwell, who was responsible for putting these ideas in a mathematical form, that electrical effects are propagated with a finite velocity equal to that of light. This celebrated deduction from theory, experimentally verified by Hertz, at one sweep brought all the phenomena of optics within the domain of electricity—one of the greatest co-ordinating advances

* Westaway, *The Endless Quest*, p. 361.

ever made in science. Indeed the efforts of Faraday to direct attention to the regions round charged bodies were so successful that the question of the atomic structure of electricity rather lapsed.

A distinguished Frenchman is reported to have remarked, on reading Maxwell's great treatise on electricity and magnetism, "I have read it all, but I don't know yet what a 'charged body' is!" It had been incontrovertibly demonstrated that an electric charge gave rise to a state of electrical strain in the medium surrounding it, but as to what the electric charge itself was, no information was as yet forthcoming.

The Discovery of the Electron.

We have seen that the atomicity of electricity was suggested by a consideration of the passage of an electric current through a liquid. The isolation of the electron as the smallest particle bearing the smallest charge followed the investigation of the passage of an electric current through a gas. The name "electron" was first introduced by Johnstone Stoney who, arguing from the laws of electrolysis, concluded that electricity was atomic and not continuous, and applied the name to "the natural unit of electricity", the quantity necessary to liberate 1 atom of hydrogen or any univalent substance. This was in 1891. Afterwards, when J. J. Thomson succeeded in demonstrating the existence of a very light negatively charged particle common to all matter, the lightest particle known, having a mass only 1/1800 of that of the lightest atom, hydrogen, and bearing the smallest charge known, the name was applied to this particle. The difference in the two meanings should be noted; the electron as we know it to-day is a particle which always bears the atom of electric charge, whereas Stoney introduced the word to denote the unit of charge, unassociated with any particle.

The Discharge Tube.

If a glass tube full of gas is evacuated by a suitable pumping system, and a potential of a few thousand volts (an electric potential is of the nature of an electric tension) is applied across the two electrodes, or terminals, at opposite ends of the tube, the phenomena observed vary with the pressure. In fact, an adequate description of all the phenomena of the "discharge tube", as it is called, is a very complicated business. Here we are only interested in one result, the most fundamental. Generally speaking, a gas is a comparatively poor conductor of electricity, but if the potential, or electric tension, be made high enough, its insulating properties break down, as, for example, occurs in a lightning flash. If the pressure of the gas in the tube is reduced it conducts more readily, and a glow suffuses the tube. What is of importance is that if the pressure be made very low indeed, say about 1/10,000 of the pressure of the atmosphere, a dark space forms near the cathode or negative terminal, and as the pressure falls the column of glowing gas becomes shorter, until eventually this cathode dark space fills the whole tube. At this stage the glass walls of the tube opposite the cathode glow with a green phosphorescent light. It is the source of this green glow of the glass which is the interesting point.

Cathode Rays.

That the green glow is due to some radiation or emanation from the cathode appears from the fact that if we put an object between the cathode and the glass, it casts a shadow (fig. 1). The cathode, then, is the source of some emanation which on striking the glass causes it to glow. At the time of their discovery, towards the end of the last century, these mysterious cathode rays aroused great interest. The problem was: what were they? Sir William Crookes gave them the name of radiant matter suggesting the possibility that matter could exist in a fourth state, besides the three ordinary states,

solid, liquid and gaseous. On the other hand, Goldstein, supported by a considerable body of opinion on the Continent, considered that they were electromagnetic waves of some kind, closely allied to light and to the then lately discovered wireless waves. As the result of many experiments,

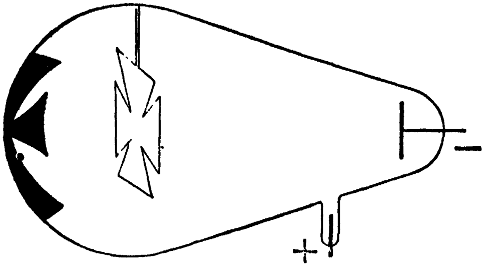


Fig. 1
From *Ions, Electrons and Ionizing Radiations* by J. A. Crowther
(Edward Arnold & Co.)

chiefly the work of Sir J. J. Thomson, the following properties of the rays were established.

1. The "rays" travel in straight lines; solid objects in their path throw a shadow.

2. They are bent by a magnetic field; this is simply demonstrated by bringing an ordinary bar magnet near the discharge tube; the beam is deflected, as may be seen from the movement of the glow in the glass. They therefore cannot be electromagnetic rays similar to X-rays, light or wireless waves; they must be particles.

3. From the fact that they are bent by a magnetic field, it follows that they carry a charge, and, seeing that they come from the negative electrode, presumably this charge is negative. This is verified by deflecting the beam as a whole by an electric field.

4. By deflecting the beam simultaneously by an electric and a magnetic field at right angles to each other, the ratio of

the electric charge to the mass, and the velocity of the par ticles, may be determined together.

5. The ratio of charge to mass is the same whatever the source of the electrons, as they are called, may be. This ratio is more than 1800 times larger than that for the hydrogen atom—it will be remembered that electrolysis introduced the idea that each hydrogen atom has a definite charge associated with it. Now this might mean that they had a mass comparable with that of the lightest element, hydrogen, and a charge 1800 times larger; on the other hand, they might have the same charge as that of the atom of hydrogen, in which case their mass would be 1/1800 that of the smallest unit known. A direct measurement of the charge alone is of course sufficient to decide the question. This measurement has been made, and shows that the charge of the electron is precisely the same, though opposite in sign, to that of the hydrogen atom, or ion, deposited from an electrolyte. The methods by which the charge has been determined will be discussed in the next chapter.

It appears then that we must accept the second hypothesis, which implies that the mass of the electron is about 1/1800 that of the hydrogen atom. The smallest unit of mass carries the smallest unit of charge, and it is common to all matter: clearly the electron is one of the fundamental bricks of the universe.

CHAPTER II

The Atomicity of Electricity

The Electron and its Charge.

In the last chapter we introduced ourselves to the electron, the smallest particle in the universe; we must now consider further ways and means of studying its properties. The discovery of the electron brought to light two important facts: (1) that atoms, the units of which matter is made up, are in themselves complex structures (cf. *The Nature of the Atom*), (2) that electricity is atomic.

We shall now proceed to discuss ways and means of measuring the charge on the electron, and of demonstrating that this charge is the atom of electricity, the unit of which all quantities of electricity are multiples.

The earliest method of determining a natural unit of charge was mentioned in connexion with Faraday's laws of electrolysis. Its identity with the unit of charge carried by the particle subsequently discovered, the "electron" as we know it, was, of course, a matter which required demonstration. A simple method of proof was found.

In the first place, if ϵ is the unit charge which occurs in electrolysis, and if by passing a current through a solution for a certain time a measureable quantity Q of charge is released, then clearly $Q = N\epsilon$, where N is the number of atoms or ions taking part. Thus, in order to find the value of ϵ, all we need to do is to determine the number N with the requisite precision.

Next, in the case of the electron, by deflection experiments

in an electric and a magnetic field the ratio charge/mass, and the velocity, were obtained, but for the actual determination of the electronic charge, recourse had to be had to other methods. Various methods were used, which, although they differed in respect of refinements and technique, were in principle identical. Finely divided water droplets—artificial clouds—were formed on gaseous ions, i.e. atoms of a gas which had lost an electron. The droplets were allowed to fall under gravity, and the total charge brought down by the cloud was measured. The size of the drops was deduced from the rate of fall. Finally, the total amount of dew deposited being determined, the average charge could be obtained. The steps in the process are: total volume of dew brought down $\div$ volume of each drop = number of drops N; total charge = $N\epsilon$: hence ϵ can be evaluated.

Such methods lead to an *average* value of the charge. Might it not be possible to measure the charge on a single drop? And although the charge is extraordinarily small, this, in fact, is what the classic experiments of Millikan set out to do.

Millikan's Experiments.

The method used by Millikan, whose experiments were carried out with extreme care, was a refined development of the method just explained. Instead of clouds of droplets, he used single droplets. His value for the electronic charge was not an average, and his method gave direct evidence of the atomic nature of electricity. The apparatus was really very simple (fig. 2). It consisted of two very accurately parallel horizontal metal plates across which an electric field could be set up, thus forming a condenser. In the top plate was a hole through which fine drops of oil could be sprayed—a scent spray may be used to produce the fine drops: a rather carefully chosen oil was used in preference to water (or mist) droplets because the latter evaporated. In the course of an experiment the motion of a single drop was followed, in some

cases for hours at a time. Throughout the experiment the size and mass of the drop remained constant.

By flashing in X-rays for an instant (or by other means—in fact, it is often sufficient just to spray in the oil) some of the drops pick up an electric charge, a free electron or a free ion attaching itself to a droplet, and through a microscope the motion of such a drop can be followed. The temperature of the whole is kept constant to prevent convection currents* of the air between the plates, which would interfere with the motion of the drops.

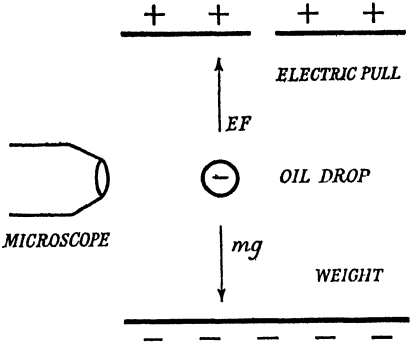


Fig. 2.—Diagram of the Millikan Apparatus

Stokes's Law.

There are on any drop two forces which control its movement, its weight and the force due to its charge exerted by the electric field. Now there is a well-known law, known as Stokes's law, connecting the movement of a drop with the force acting on it. In its simplest form, the law states that the velocity of any particular drop is proportional to the force acting on it.

* A convection current is a movement of the air, a wind, set up by temperature differences in the air.

We may therefore write: $v = kP$, where v is the velocity, P the force, and k a constant.

1. If the drop falls under gravity alone, $v_g = k \cdot mg$, where m is its mass, and g the acceleration due to gravity.

2. If a field is applied tending to stop the drop, pulling it up against gravity, then E being the charge on the drop and F the field, the new velocity is $v_F = k(mg - EF)$, since a charge E in a field F is acted on by a mechanical force of value $E \times F$.

Thus, by simple algebra,

$$\frac{v_F}{v_g} = \frac{mg - EF}{mg} = 1 - \frac{EF}{mg},$$

or

$$\frac{EF}{mg} = 1 - \frac{v_F}{v_g} = \frac{v_g - v_F}{v_g}.$$

The velocities were easily determined by measuring the time taken to move over a scale, which could be seen when the drop was watched through the microscope placed at the side of the condenser. Certain complications appeared, and certain refinements were necessary, but the above treatment gives the essentials on which the experiment is based. By adjusting the field suitably, allowing a drop in the field of the microscope to fall under gravity, and then applying an electric field to pull it up again, the movement of a single drop could be followed for a long time. Occasionally it was noticed that the steady rise or fall of a drop was interrupted by a sudden increase or decrease in the motion, which might be interpreted as the gaining or losing of a unit of charge, the gaining or losing of an electron.

Direct Evidence of Atomicity.

The most noteworthy result of the experiment was the fact that the charge E on the drop, which could be calculated, was always an integral multiple of a certain definite charge. In other words it was found that E was always of the form

$E = ne$, where n is a whole number and e a deduced constant charge. No charge was ever obtained smaller in value than e, and every charge was of value e, $2e$, $3e$, and so on. The natural conclusion, then, is that here we have direct evidence of the atomic or granular structure of electricity. But it should be pointed out that, although this affords explicit evidence of the atomic nature of electricity and permits of the measurement of a unit of electric charge, it still remains to identify this unit with the charge on the electron, denoted above (p. 11) by ϵ. The difficulty, however, is easily got over, for the electronic charge must either be the e found by Millikan, or some integral multiple of e. The question is therefore settled if we know a rough value of the charge on the electron; and this was obtained before Millikan's experiments were carried out, by allowing a large number of electrons to build up a charge Q which could be measured by direct electrical means, and dividing by the (roughly) known number of electrons. The evidence is complete—the charge on the electron and the unit of electrical charge found by Millikan are identical, and the single symbol e may now be used for both.

Mass of the Electron.

The charge on the electron being now known with precision, the deflection experiments on beams of electrons in an electric and magnetic field, which determine the ratio charge mass, permit us to calculate the mass of the electron. The actual values of the charge and mass of the electron are of course very small. The value of e, the unit of charge, is $4{\cdot}80 \times 10^{-10}$ electrostatic units; that of m, the mass of the electron, 9×10^{-28} gm. Such values are small almost beyond comprehension, as is to be expected; were it not so, the granular nature of electricity would have been realized much earlier. The mass of the electron is about 1/2000 that of a hydrogen atom, which is the lightest known element, and, until the discovery of the electron the smallest mass known. As regards the charge, an ampere, which is the unit of cur-

rent commonly used, passing through a circuit requires every second the passage of about 2×10^{19} electrons, that is 20 times a million times a million times a million electrons.

It must be mentioned here that refined experiments have brought to light the fact that the mass of electrons varies with their velocity, increasing as the velocity increases. The increase is insignificant, however, except at very great speeds, comparable with the speed of light (186,000 miles per second). This variation of mass is in agreement with Einstein's Special Theory of Relativity, and, in fact, is not a property peculiar to electrons, but is common to all matter.

Radius of Electron.

As regards the size of the electron some difficulty arose, as the size had to be deduced theoretically. The deduced value of the radius of the electron, assuming the shape to be spherical, a value in the neighbourhood of 10^{-13} cm., gives an idea of the scale in which we must think when we consider electrons. This value of 10^{-13} cm. is of about the same order as that of the nucleus of an atom, about 1/100,000 of the radius of an atom. We shall see later, however, that the meaning to be attached to such a quantity as the " radius of an electron " must remain somewhat vague.

Electron Spin.

It was found necessary to attribute " spin " to the electron, i.e. to suppose it capable of rotation about an axis within itself. Two lines of argument led to this conclusion. The study of the line spectra of the elements (cf. *The Nature of the Atom*) elicited the fact that many lines have a multiplet structure, that is to say, consist of a group of closely spaced lines, the multiplicity being the number of lines in such a group. The general characteristics of the line spectra of the elements received an explanation on certain hypotheses of Bohr, but careful consideration showed that there were still some points which remained unexplained. For instance, the spectrum of

sodium, which may be studied by examining the emission of common salt heated in a flame, showed a very strong yellow line which proved to be double, that is, to consist of two lines very close together. It was found necessary, in order to explain why this line was double, to assume that the electron had a spin.

The second source of evidence which led to the hypothesis of a spinning electron (first put forward by Uhlenbeck and Goudsmit in 1925), is associated with the magnetic properties of atoms. We have seen that an electric current gives rise to an associated magnetic field, so that an electric current moving in a closed circuit possesses properties similar to those at a magnet (fig. 3). It is therefore natural to suppose that the magnetic properties of atoms should be connected in some way with electricity in motion. We have not far to look for the electricity, since electrons are constituents of all atoms.

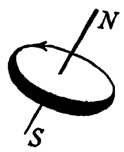


Fig. 3

It is therefore not surprising that the electrons in atoms should have been found to behave in some respects like little bar magnets. It was concluded that atomic electrons had a magnetic moment, which was interpreted as evidence that the electron spins round on its axis. If we picture the electron as a tiny sphere with the electronic charge distributed over its surface, we see that by imagining this model to spin, we obtain a charge moving round a closed circuit and hence a small magnet.

The new picture of the electron which the evidence of a wave structure leads us to build up, evidence which we shall discuss in Chap. V, throws new light on this spin of the electron, and modifies our view considerably. Meantime we may note that the concept of electron spin is derived directly from experimental evidence and is a necessary adjunct to our picture of a particle electron, required to explain certain details of spectra and the magnetic properties of atoms.

CHAPTER III

Particles and Waves

Part I. Particles

Having now given some account of the simple or particle electron, explaining how its existence was first demonstrated, and pointing out the properties it was found necessary to associate with it, we must make what appears at first sight to be a complete digression. In the next chapter we shall discuss the evidence that leads to the conclusion that the concept of the electron as a hard particle of definite minute dimensions is inadequate, so that the particle picture breaks down. Then in the following chapter we shall explain why it has been found necessary to bring in the idea of waves. Preparatory to this, however, we must consider in some little detail the intrinsic properties to be expected of a stream of particles, and make clear what precisely we mean by a wave motion. We must also explain how a wave can be recognized, and in what ways it may be discriminated from a stream of charged particles. Throughout this chapter we shall use various phenomena of light as illustrations.

Propagation of Energy.

The crucial question is: how is *energy* propagated? If we have a source of energy at A, for instance, a wireless transmitter, and a mode of detecting or absorbing either all or part of this energy at B, we wish to inquire in what way and under what conditions the energy passes from A to B. At first sight there appear to be three methods by which the problem might be tackled:

1. By considering how the energy is ejected or emitted from the source.

2. By considering what goes on in the space between A and B.

3. By considering how the energy is absorbed.

The physicists of last century devoted considerable time to deducing the properties of what they called the " luminiferous ether ", the medium supposed to be responsible for the propagation of light, but the properties it was found necessary to attribute to it appeared so strange and paradoxical that the ether fell into disrepute. Moreover, various attempts made to detect its presence directly (e.g. the Michelson-Morley Experiment) all gave a negative result. Of late the emphasis has been shifted: relationships deduced from theory have gone out of favour in comparison with actual observation.

If we think about the matter it will become clear that experimental demonstrations of how energy of any type, electromagnetic or other, is propagated necessarily imply some form of detection, and this immediately involves the third of the three methods just mentioned. What can be observed is what happens at the source and at the receiver; we then deduce the behaviour in the intervening space as consistent with these observations. We shall see that the characteristic properties of a wave propagation are that the distribution of energy in space should, at the detector, display a certain periodic pattern, which is not only *not* characteristic of a particle propagation, but even inconsistent with it. If, then, we observe such a periodic pattern, we conclude that the propagation of the energy is by means of some type of wave mechanism.

Streams of Particles.

We shall consider particle propagation first, since its properties are so simple as to be obvious. In illustrating various properties of streams of particles by comparing them with

those of light, we reverse the chronological order, since the wave theory of light had been accepted for years before certain phenomena connected with the energy interchanges between matter and radiation (i.e. light) rendered some sort of particle hypothesis necessary. These are the phenomena we shall cite in this section. It must also be observed in advance that we include under the term light the complete electromagnetic spectrum (fig. 4); in the present section we shall be concerned more particularly with phenomena associated with radiation of the type of X-rays and γ-rays.

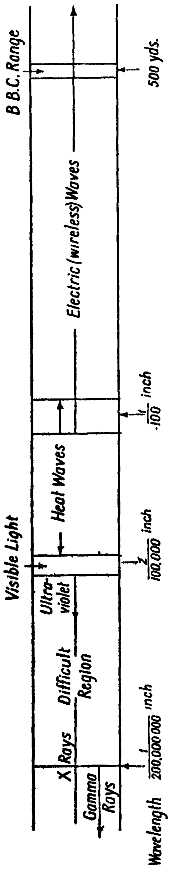
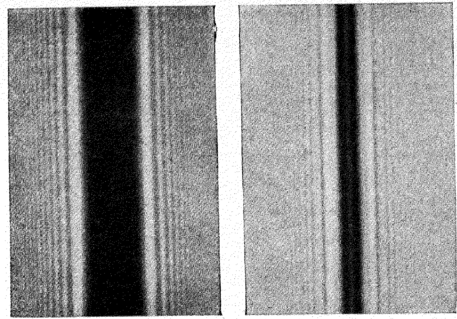


Fig. 4.—Range of the Spectrum: equal distances correspond to equal ratios of wave-lengths
From *The Atom*, by G. P. Thomson (Thornton Butterworth)

Probably the most obvious characteristic of particle propagation is that free particles move in straight lines. " Every body continues in its state of rest or of uniform motion in a straight line, except in so far as it is acted on by some external impressed force " (Newton's First Law of Motion). If no " external impressed force " acts, the particles in a beam continue to move in a straight line. We cannot fire a bullet round a corner. As a result sharp geometrical shadows are formed by screens set up to cut off the beam. It was this simple fact that led Newton to subscribe to a particle theory of light.

It appears that light travels in straight lines, that it forms sharp geometrical shadows, that " we cannot see round corners ". On the other hand, if we watch the ripples on a water surface, we see that they do bend round corners (figs. 5 *a* and *b*). It was later demonstrated



Horse hair Human hair

Fig. 7.—Diffraction by small obstacles

(From *Handbuch der Physik* (Springer))

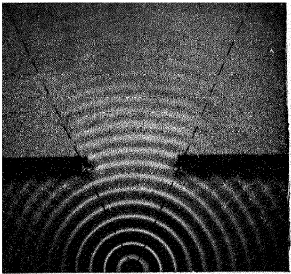


Fig. 5*a*.—Diffraction through a wide slit

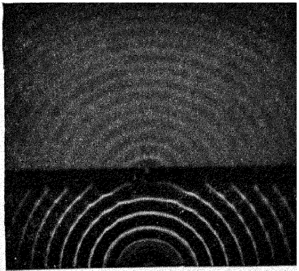


Fig. 5*b*.—Diffraction through a narrow slit

that light also to a certain extent bends round corners, that the geometrical shadows are not sharp but are of varying intensity at the edges, and Newton's argument was rendered invalid.

If we double the number of particles emitted by the source, the effect at the detector is doubled. If a machine gun fires twice as quickly, twice as many bullets will hit the target. This may seem to be very much a case of labouring the obvious, but we shall see when we come to consider wave propagation, that this simple property allows a very important distinction to be drawn between particles and waves. In some cases, in fact, by doubling the amount of light we may get darkness, owing to interference, as it is called, a palpable case of two whites making a black.

Part II. Waves

I asked a member of the lay public on one occasion what he understood by wave motion. He frowned and looked worried and, waving his hand up and down, said, " Oh something—ah—something that you can see and that goes up and down." Atomic phenomena are on a very minute scale, and we are faced with the problem of recognizing a wave motion in cases when we cannot see anything " going up and down ". However, we can start with something we can " see that goes up and down " and, under less restricted conditions, consider those particular features which constitute the " waviness " which can be recognized.

When we drop a stone into a pond the ripples spread out from the place where it was dropped in, and a cork near the edge of the pond bobs up and down as the ripples reach it. We can say that dropping the stone into the pond has caused the cork to move up and down, but there has been no direct contact between the stone and the cork. The only link between them is the intervening water, but the water has not

transferred the stone to the cork, and, in fact, if we look closely we can see that the water itself at any place does not move far from its original position, though it has transferred the up-and-down motion to the cork. The energy has been transferred to the cork not by reason of any material particle or substance travelling from the place where the stone was dropped in, but because the up-and-down motion of the water has travelled out to the cork. This is probably the simplest example of transfer of energy by a wave, a water wave which travels over the surface.

Interference of Waves.

We can learn quite a lot about the properties of wave motion by considering these waves which travel over the surface of a liquid. Fig 6*a* shows the waves spreading out over a pond when we drop a stone into it. It may happen that we have two such wave trains; what happens then at those places where they cross? Fig. 6*b* shows the result of two wave trains spreading out, the sources of the waves being the two balls in the photograph. Obviously if at any point one wave train tends to produce a hump and the other tends to produce a hollow, we should expect no displacement of the water to occur there at all. This is precisely what does happen. The one wave train is, as it were, superposed on the other, and the two wave trains are said to "interfere": in fig. 6*b* the spoke-like regions of still water are places where the two waves destroy one another. The "interference" or crossing of two wave trains does not affect the subsequent progress of either. The light which enters the eye, reflected say from a table, is quite unaffected by the fact that it has crossed innumerable other wave trains on the way; if it were not so, we should not obtain any clear impression of the table at all. This principle of interference is fundamental to all wave motion; it is to this we referred when we said that two whites occasionally do make a black. Two wave trains in certain places nullify each other.

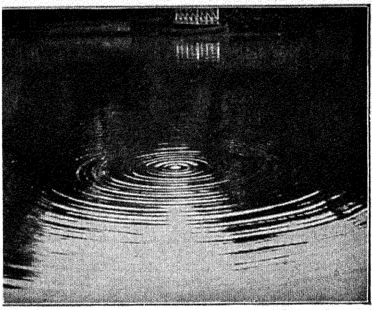


Fig. 6*a*.—Circular waves

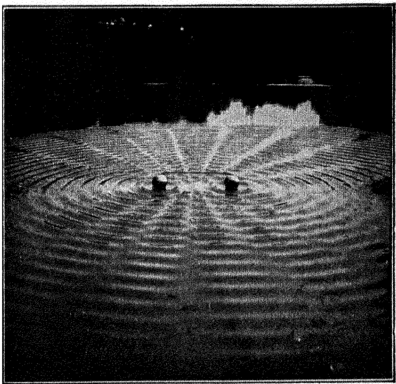


Fig. 6*b*.—Interference of two circular water waves

Diffraction.

If the wave train passes through an opening in a screen, it will be seen that on the other side from the source, the waves spread out round the corners, so to speak (fig. 5). Even if a given point be screened from the source, so that it lies in the geometrical shadow, it may still be subject to disturbance by the waves. This spreading out of waves as they go through an aperture is known as *diffraction*. The narrower the opening, the greater the spread.

Waves in General.

We have discussed waves on a water surface at some length because they afford probably the commonest examples of wave motion. We shall now turn to waves in the abstract, and consider properties common to water waves, sound waves, and light waves—properties of " waviness ".

In the waves we have hitherto discussed the characteristic feature has been an up and down motion which moves out from the source. The important questions are:

1. how fast does the wave move out from the source—the velocity of propagation;
2. at what rate does the up-and-down motion repeat itself—the frequency;
3. what is the distance between any crest (or hollow) and the next crest (or hollow)—the wave-length.

A wave train is a recurring fluctuation, periodic both in space and time. That is to say, if we consider a train of waves *at any given instant*, if, for example, we imagine the water in the previous examples suddenly frozen, the profile of the surface is of the form of the line shown (fig. 8*a*).

In other words, the same state of affairs, state of humpiness, let us say, recurs at equal intervals along the wave. The state of humpiness, varying according as the displacement from the normal level is at its highest or lowest or at some stage in between, is known as the *phase*; and the

distance between two points of identical displacement, i.e. of the same phase, is the *wave-length*. This is what we mean when we say " a wave is periodic in space "

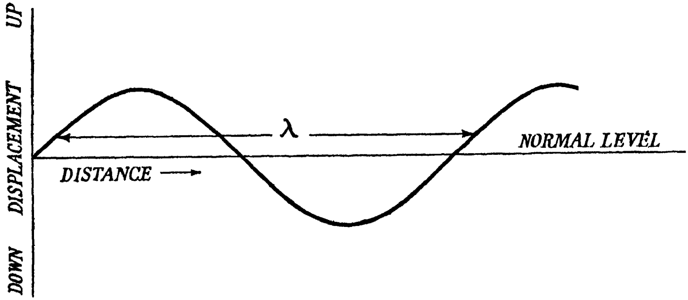


Fig. 8*a*

Now consider what happens *at any given point* as time passes. The motion at the point is represented by the same type of curve as before (fig. 8*b*). As time elapses the matter —water or mercury, or whatever it is that is vibrating—is

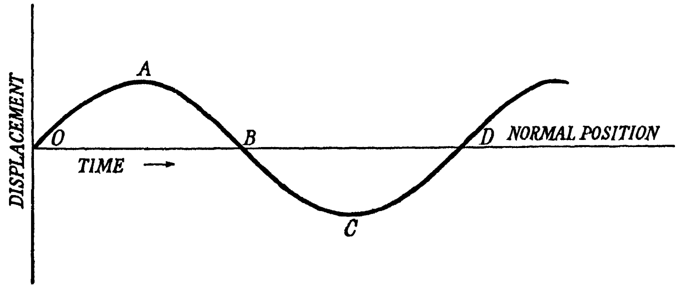


Fig. 8*b*

displaced from its original undisturbed position, moving gradually farther and farther away from this normal position O until it reaches a maximum displacement A known as the *amplitude*. It then returns and, because the medium is elastic —a condition of wave propagation is that the medium must be elastic, that is, if we distort it in any way it tends to return

to its original form—it moves right through its original position again (B) and is displaced in the opposite direction to C, then back again to D. This state of continuous oscillation goes on, so long as the wave train continues to pass.

Two Types of Wave.

The direction of the displacement may or may not be the same as the direction of propagation of the wave, and from this point of view two important types of wave can be distinguished: (1) compressional waves, in which the particles of the medium are displaced to and fro, in the same direction as that in which the wave is moving—this is the case of sound waves, which are compression waves in the air; (2) waves in which the displacement is at right angles to the direction of propagation, or, as we may express it, out and in. This is the case of light waves.

It may be natural to conclude that if we have a case of wave motion, they must be waves of something, something must vibrate. This was the feeling that led the physicists of last century to think so much about the " luminiferous ether ". Really, however, what is of primary importance for the matter in hand is that a certain behaviour is consistent with wave motion; the question of what is vibrating is, as we shall see, of secondary importance, and in some cases is very difficult to answer.

Transverse Waves in a Cord.

Now let us try to link up these two notions of periodic fluctuation in space and in time. If we have a long cord of tight rubber and flick one end we displace a part of the rubber, which pulls the next piece, this again pulling the next piece, and so on right along. Meanwhile, when the first piece has reached its maximum displacement it moves back towards its original position, where it arrives with a certain kinetic energy, which carries it on to the opposite side, and so the rhythmic motion proceeds. An analogy given by Westaway

in *The Endless Quest* may help: "The successive movements of the particles of a transverse wave may be simply illustrated. Let fifty or sixty boys form a single-file column, standing one behind the other at intervals of about a foot. A chalk line will serve as a convenient guiding line. Let the order be given for every boy to move three paces to the right, then three paces to the left (i.e. back to the starting-point) then three more paces to the left, then three to the right (i.e. again back to the starting-point), and so on indefinitely until a halt is called. The boys are to move *in succession.* A takes one step alone; when he takes his second step, B takes his first; when A takes his third, B takes his second, and C takes his first. And so on. Time may be kept by the beating of a drum. Watched from an upper window, the forward travelling wave along the line of boys is most impressive, and it is easily seen that any and every element of the wave (i.e. any and every given boy) is simply moving to the right and left, i.e. transversely. The illustration is imperfect in one important feature; in a medium carrying a real transverse wave, the particles are in some way connected, so that when one is moved it drags its neighbour with it."

Dispersion.

If a source emits n waves per second, so that the particles of the medium vibrate n times a second, and if the wave-length is λ, then each particle must, so to speak, hand on the wave a distance λ, to be ready for its next vibration, n times a second. During each second the wave therefore travels a distance $n\lambda$, so that the velocity of propagation C (say) $= n\lambda$.

In certain cases the velocity of propagation is not the same for every wave-length. This is so in the case of light passing through glass. Red light travels faster through glass than blue light; this is why a prism spreads white light into a band of colour or spectrum. The phenomenon is known as *Dispersion*.

Groups of Waves.

We have now explained the main features involved in the notion of a wave. We have stated what is meant by the *frequency*, the *wave-length* and the *velocity* of the wave. We began by considering ripples on a water surface, and passed on to consider waves in the abstract. We shall have more to say of these—our discussion of their properties is far from complete. The picture, indeed, is too simple. As is often the case, the simplicities of experiment are far from being the simplicities of theory. Generally speaking, in fact, it is the corrections that have to be applied in order that the conditions of the theory may correspond nearly enough with the conditions of the appropriate experiment, that are the source of most of the trouble in scientific work.

The type of picture we have sketched, more rigidly defined and discussed in mathematical books as a " sine wave ", has associated with it a definite wave-length λ; indeed, such a wave is completely defined by stating the wave-length, frequency, and amplitude (or height of the humps). Now we may have two or more of these waves of different wave-lengths moving in the same direction, and, in fact, this is the common case. The perfect, ideally simple wave of theory does not exist in practice; instead of this we find groups of these waves superimposed.

Perhaps the most striking example of the superposition of wave-motions is seen in an orchestra. Sound is a wave motion of the air, the instrumental source setting the air into vibration, the wave travelling out, striking the ear and setting the appropriate nerve endings into sympathetic vibration. Each instrument in the orchestra sends out its own waves and all these waves are superimposed on one another. They do not meet for the first time in the ear of the listener—they travel out together across the hall.

If we watch the ripples on a water surface closely when we drop in a stone, we shall of course notice the disturbance

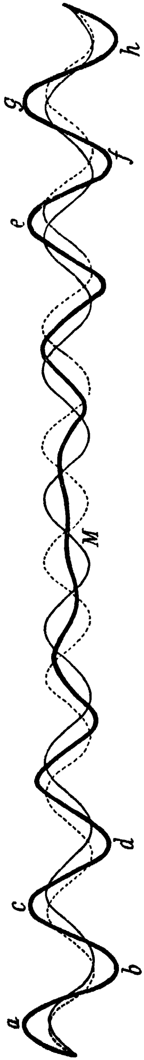


Fig. 9.—Superposition of Waves of Frequencies 8 and 9 respectively. The thin lines represent the components, the thick line the result of their superposition. (From *Sound*, by J. H. Poynting and Thomson: Chas. Griffin & Co., Ltd.)

moving out from the place where the stone was dropped in, but we shall also see little individual waves moving across the surface of the water, advancing through the main disturbance and dying out in front. Indeed, the main disturbance is simply a region where the little waves add up, while the smooth region lies in those places where they destroy one another. The main disturbance is due to movements of the group of waves as a whole, and from the fact that the individual waves move up to the group, and through it, we conclude that the speed of the group is not, in this case at least, the same as that of the individual waves. Any wave disturbance, of whatever nature, water wave, sound wave or light wave, is not a simple " sine wave ", but the movement of a group of such waves which, when superimposed, give the disturbance observed. The speed of the individual waves may not be the same, for waves of different wave-length may under certain circumstances have different velocities. In these cases the speed of the group may be quite different from the speed of any individual wave (cf. fig. 9).

Light behaves as a wave phenomenon, and the light of the sun contains components of different wave-lengths. The effect of difference of wave-length in the case of light is a difference of colour; red light, for instance, has a wave-length

about twice as long as that of blue light. Ordinary white light is a mixture of all the colours of the spectrum or rainbow. It may be split up into its component colours in various ways, by a prism, for example. A rainbow is caused by the splitting up of light by droplets of water in the atmosphere.

Stationary Waves.

If we take a rope and fasten one end firmly, and move the other end rhythmically backwards and forwards so that a wave is propagated along the rope, we shall find that this wave is "reflected" from the fixed end. When the wave disturbance has moved along the rope to the fixed end, where of course the rope cannot move, the effect of this fixed end is to give rise to a wave travelling back in the opposite direction, a reflected wave. Finally, then, the movement of the rope is controlled by the two factors, the two waves travelling in opposite directions along it. If the experiment is carried out carefully, a curious kind of motion is set up known as a *stationary wave*. The effect of the reflected wave combined with the initial wave at the fixed end is just such as to leave the fixed end at rest, but it will be observed that there are other points, recurring at regular intervals (each equal to half the wave-length) along the rope, at which the rope does not move at all, or in other words, is *stationary*. These points are called *nodes*, and are the points at which the two waves permanently destroy one another, where at any instant the displacement which the initial wave would cause is destroyed by that due to the reflected wave. The reader is advised to study fig. 10 carefully. Superficially there appears to be nothing moving forward, the rope appears to be swinging backwards and forwards rhythmically.

Stationary waves are of great importance. In an organ pipe the instrument sets up stationary waves in the pipe, and these are the source of the wave train that reaches the ear; in a wireless receiver the incoming wave (from the transmitter) sets up stationary waves in the aerial circuit, which

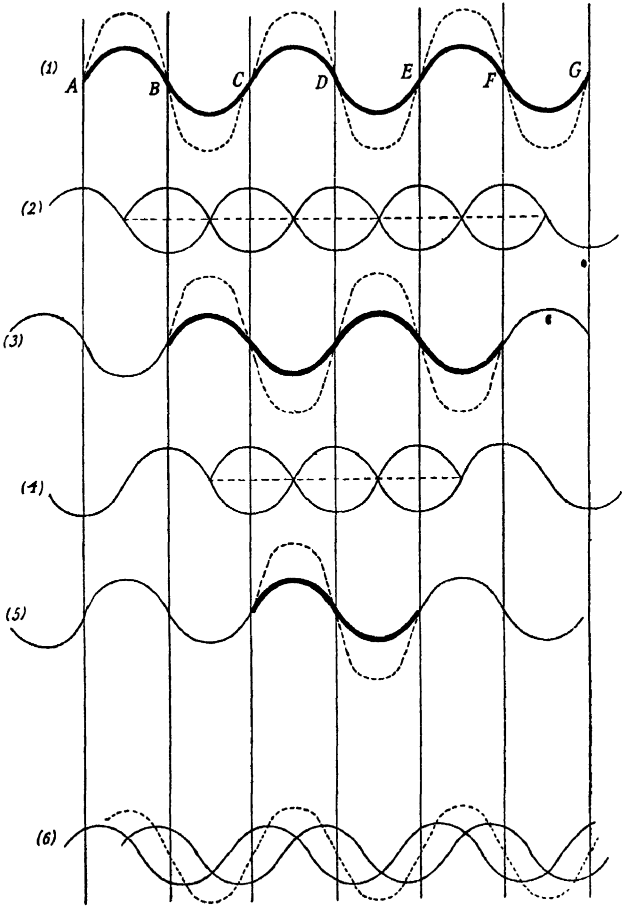


Fig. 10.—Formation of Stationary Waves by opposite motions of equal trains. (1) The two trains coincide, and each is represented by the black line; their resultant is represented by the dotted line. (2)–(5) Positions at successive intervals of $\lambda/4U$, the dotted line always showing the resultant. (6) A position intermediate between (1) and (2), showing that the nodes are always fixed.

(From *Sound*, by J. H. Poynting and Thomson: Chas. Griffin & Co., Ltd.)

we amplify and listen to. The difference between a stationary wave and a progressive wave is that while in the latter all the vibrating points or particles go through the same cycle, in the former only those separated by half a wave-length have the same amplitude of vibration.

We shall have more to say about stationary waves later.

Interference.

The first conclusive proof of the wave nature of light was the interference experiment of Young, in which two beams

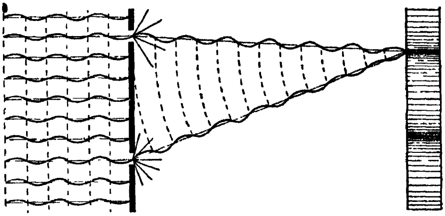


Fig. 11

of light coming from two slits interfered with each other, so that at certain places the two whites made a black. If a plane wave, that is, a wave in which all points of equal phase lie in a plane, falls on two narrow slits, the slits become effectively sources of waves. If we place a screen behind the slits, the illumination of the screen comes from both slits simultaneously, and the pattern which appears is the result of the interference of the two beams.

If we consider any point in the screen distant a from one slit and b from the other, then the beam from the second slit has travelled a distance $b-a$ farther than the beam from the first. Now the waves which come from the two slits are in phase at the slits; the plane wave is at exactly the same stage in its career when it reaches the two slits—that is why we chose a plane wave for our illustration. It follows that if $b-a$ is an integral number of wave-lengths, the two beams are in

phase at the point in question, and therefore add up. If, however, $b-a$ is an odd integral number of half-wave-lengths so that when the first slit produces an " up ", the second produces a " down ", then there will be darkness. The screen will therefore be crossed by a pattern of alternately light and dark lines. The argument is illustrated in the diagram, but the reader is advised to draw out the wavy lines for himself and check the above argument.

The question whether there is brightness or darkness depends on the value of $b-a$ expressed in wave-lengths; of course if this is neither an integer nor a half integer, the illumination is something between the brightest intensity and complete darkness. The dimensions of the pattern, or the distance apart of the bright lines, clearly depends on the wave-length. The shorter the wave-length the finer the pattern. If the incident light is not all of one wave-length, but consists of many wave-lengths—if it is white light, for example—the various components or colours form their own patterns and the resultant pattern is coloured. A similar explanation can be given of the colours of the thin films of oil on the puddles of water on the road; in this case the waves interfere with themselves, i.e. the wave reflected from the top surface of the oil interferes with the fraction of light reflected from the lower surface.

Diffraction.

We have seen that ripple waves bend round corners; the narrower the slit through which the waves pass, the greater the bending round the corner. Moreover, it appears that the smaller the wave-length, the less obvious the effect; in fact, if the slit is large compared with the wave-length, the waves to all intents and purposes travel in straight lines, the spreading or diffraction being dependent on the ratio λ/a where λ is the wave-length and a is the width of the slit. To show the bending of light, then, the slit must be narrow, for the wave-length is small. This effect of spreading or " diffraction "

as it is called, also occurs if we use obstacles or screens of the appropriate size. Fig. 7 (p. 20) shows the broad pattern given by light diffracted by fine threads of hair (cf. also fig. 5, p. 20). The reader is advised to try the experiment of looking at a strong source of light through the cracks between the fingers of his hand held up close to one eye, the other eye being closed. With little difficulty he will obtain a spread-out pattern of coloured light.

X-rays—Particles or Waves.

When Röntgen at the end of last century discovered X-rays, a controversy at once arose as to whether the rays consisted of particles or were of a wave nature. In the early experiments they appeared to show none of the characteristic properties of waves. Haga and Wind as early as 1899 had used a wedge-shaped slit, a few thousandths of a millimetre broad at its widest end, and noticed that the faint image received on a photographic plate was *broader* opposite the *narrower* end of the slit, as was to be expected if the rays were of a wave nature. The experiments, however, were not satisfactory, although the estimate of the wave-length to which they led, viz. that 200 million wave-lengths are required to make up 1 in., was subsequently shown to be of the right order of values.

Diffraction Grating.

To understand the later experiments which were accepted as giving incontrovertible evidence of the wave nature of X-rays, we must consider an instrument known as a *diffraction grating*. This consists of a surface of glass or metal on which are ruled a series of very fine lines, thousands to the inch. The instrument depends on the principle that light coming through a slit will bend round corners, and here we have a very large number of slits.

The diagram shows such a grating in profile. The important feature is that it consists of a regular series of alternately transparent and opaque strips. If a plane wave falls on this

grating as shown, each slit will give its own pattern and the total effect on a screen placed to receive the resultant pattern will depend on how these individual contributions add up. We have already (p. 31) considered roughly the case of two slits. If we consider the light diffracted in a given direction θ to the incident beam (fig. 12), it is clear that the points A, B, C, D, E, . . . are corresponding points on their respective slits, and that all the slits can be divided into series of small parts such as those at A, B, C, D, E. . . . Now, if the difference of path, for the beams going in the direction θ, from A and from B is λ, the corresponding difference for A and C will be 2λ, and so on. The contributions of all the slits will therefore add up, and we shall have a strong maximum in that direction.

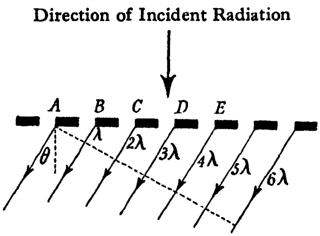


Fig. 12

The reason for using a large number of slits is that the larger the number of slits, the narrower the maxima; and if we have light of two different wave-lengths present, each of which gives its own pattern, then the narrower the maxima, i.e. the finer the pattern, the easier it is to discriminate. At first no evidence was found that a diffraction grating gave a pattern with X-rays. Later more highly refined work, using beams at grazing incidence, has demonstrated that an optical grating can be used to show diffraction of X-rays. The difficulty in the earlier work was precisely that of Newton, for the X-rays appeared to be propagated in straight lines; there was no diffraction because the grating was too coarse, i.e. the slits were too wide.

Crystal as a Grating.

The essential property of a grating is that it has a regular structure, so that at exactly equal intervals of its length equal

contributions are made to the final intensity, the result depending on the way in which the contributions are added. The difference in the path from two neighbouring elements to a point on the screen decides the effect at this point. Von Laue had the brilliant idea of replacing the grating by a crystal, which is a regular grouping of atoms in space. When an X-ray, or any electromagnetic wave, passes over the crystal, the atoms are set into oscillation by the wave and act as sources of scattered waves. Thus the atoms act as scattering centres in exactly the same way as slits, and it is the manner in which these scattered beams add up which gives the crystal diffraction pattern. In the grating the lines are ruled on a plane face, whereas in the crystal the atoms are arranged in three dimensions, so that it is somewhat difficult to work out the pattern to be expected from a given crystal. A simple solution of the problem was given by W. L. Bragg, who showed that the patterns could be deduced by considering the reflection of the rays by planes of the crystal lattice.

The acid test of wave propagation is the regular pattern obtained by using a regular or periodic screen, the dimensions of which must be comparable with the wave-length. No pattern is obtained if the propagation is of the nature of streams of particles or if the dimensions of the screen are too large. If the characteristic pattern is obtained with a suitable screen, a wave mechanism is at work.

CHAPTER IV

The Failure of the Particle Electron

Introduction.

The non-technical reader will probably find this the most difficult chapter in the book, unless he happens to have read the volume in this series on *The Nature of the Atom*, in which case the present chapter should be found fairly easy. What we shall try to do is to explain the reasons why, about 1924, physicists were looking for such a property as a wave-structure for the electron—why it was felt that the particle picture then current was unsatisfactory. In the next chapter we shall discuss the direct incontrovertible experimental evidence that the electron has a wave-like structure. Omission of the present chapter in its entirety involves then no handicap as far as the later chapters are concerned; it is necessary in the logical development since it led to the experiments being made, but once they were made, the evidence they gave stands on its own feet independently of any background.

Atomic Structure: Defects of Bohr's Theory.

The early successes of the Bohr picture of the atom distracted attention from critical analysis of the basis on which the theory rested. It is true that direct experimental evidence was forthcoming (experiments of Franck and Hertz) on the existence of electron energy levels in the atom, the energies of which could be evaluated. The energy differences obtained, and the frequencies which appeared in the line spectra, could be used to check Bohr's fundamental hypothesis:

Difference in energy of electron in initial level and final level $= h\nu$;

where h is Planck's constant, and ν is the frequency. A relationship of this type was found to run through all matter-radiation energy changes, and was consistent with the group of phenomena which called for a photon (or particle) theory of light. But in the most elementary of atom models, one may look for some reasoning to be put forward showing *why* the electrons are distributed in levels or orbits of different energy values. The Bohr theory merely asserts boldly that they do, and it must not be forgotten that the assertion is flatly contradictory to the theory which had hitherto been held to describe the motion of electrons. Considered as a fact, it was too sophisticated to be expected to stand as one of those " fundamental facts " on which a theory is based. It was natural to expect that in time, with the refinement of the theory, an " explanation " or simplification of these electron energy levels would be forthcoming.

The second feature one notices on examining a line spectrum, after observing its line structure, is that the various lines are of different intensities; and after it has been explained or demonstrated how the various frequencies may be derived, the next problem might naturally be taken to be the evaluation of the relative intensities of the lines. An attempt was made to solve this problem by means of what was known as the *correspondence principle*. This principle was also used as a physical basis for the " selection rules ", which are simple rules derived in the first place by trial and error from the experimental results. The results for the selection rules were unsatisfactory, and those for the relative intensities did not agree with experiment.

Certain details of line spectra appeared which did not at all fit into the general scheme; indeed, it soon appeared that the Bohr picture of the atom, while providing a remarkably clear first approximation, did no more than that. The final picture must of necessity be more elaborate. In applying Bohr's theory to atoms of high atomic number, admittedly the calculations were bound to be approximate, but certain

difficulties appeared which were fundamental. Indeed, refined observations showed that Bohr's theory was incomplete even in the case of the simple spectrum of hydrogen, for it predicted for the fine structure of one hydrogen line three lines where five were actually found.

Fine Structure of Spectra.

Close investigation demonstrates that what appears at first sight to be a single line may in fact consist of a group of fine lines. The original line has what is known as a *fine structure*. This, of course, implies an analogous fine structure, or multiplicity, of the energy levels. Relativity theory predicts, and experiment confirms that the mass of a moving particle varies with its velocity, the variation only becoming appreciable when the velocities are very high (of the same order as that of light). Sommerfeld investigated the effect this would have on the motion of an electron round a nucleus, and so found a theoretical basis for the observed fine structure. His formula showed at first sight a remarkable—though, according to the view now accepted, fortuitous—agreement with the facts, but it was found that there were serious discrepancies.

Molecules.

The picture of the binding together of atoms to form molecules was also inadequate. It was supposed that certain atoms might lose an electron easily to become positively charged, while others might acquire a loose supernumerary electron to become negatively charged. The charged atoms would then attract each other, and the binding of the two atoms is thus accounted for. Cases were known, however, where no such process took place. Further, the banded spectrum of diatomic molecules was observed to lack a band in the centre of the band pattern, an experimental fact which did not receive adequate explanation until the wave picture of the electron was forthcoming.

Conduction in Metals.

The fact that metals are good conductors of electricity compels us to believe that there must be in the metal a very large number of *free* electrons, that is, electrons unattached to atoms. When a potential difference, or electric tension, is applied across the ends of the metal, these electrons move at once under the action of the potential difference, or, in other words, a current flows. It was to be expected that such a large number of free particles would contribute to the specific heat of the metal—but no such contribution was observed; for specific heat calculations the electrons did not appear free, for electrical conductivity purposes they must be free. Moreover, the calculated ratio of heat conductivity to electrical conductivity, a ratio of theoretical importance known as the Wiedemann-Franz ratio, did not agree with the observed value.

Other Difficulties. Electron Diffraction.

The emission of particles, α-particles, for instance, by radioactive bodies was another outstanding experimental fact which, until it was realized that all particles must be conceived as having a wave structure, completely defied explanation.

We might go on adding to the list of difficulties indefinitely; the idea of spatial quantization and the explanation of the Zeeman effect were unsatisfactory; experimental results made it necessary to introduce half integer quantum numbers; anomalies were observed in the specific heat of hydrogen at low temperatures; many observed facts were in disagreement with the theoretical predictions. We need not go into these points in detail; it suffices to realize that there were difficulties, hosts of difficulties, until, in 1924, it was felt that an impasse had been reached. It must be pointed out, however, that all these quoted facts and relationships do not indubitably point to the wave nature of the electron. If they

did, it would surely have been discovered earlier; but they were sources of difficulty, raising questions to which the theory of the day could give no satisfactory answer. It was felt that some radical and far reaching advance was imminent, but he would have been a rash man who believed that that advance would clear up at one sweep all these difficulties. Many of the examples quoted appeared quite unrelated, yet as it has turned out the explanation of some has, in many cases, immediately led to the clearing up of others.

Light-Waves and Particles.

Newton thought that light consisted of a stream of particles for light travelled in straight lines. It was shown, however, that in certain cases light bends round corners—the experiment of looking at a bright light through the slits between one's fingers shows this—hence the conclusion that it must be of the nature of a wave motion. The characteristic properties of wave motion are shown by light; beautiful interference experiments supported the wave hypothesis, the characteristic regular diffraction patterns verified it, and in fact at the end of the last century no one for one moment would have claimed that any optical phenomenon could not be described by a wave mechanism. The distribution of light in space is in all cases a wave distribution.

During the first quarter of the present century, however, various phenomena were discovered which are quite inconsistent with a wave mechanism, but fit in admirably with a picture of light as a stream of particles. All these phenomena are associated with the energy interchange between matter and radiation, that is to say, while the distribution of the light is completely governed by waves, yet, when light is absorbed by matter or emitted, it does so after the manner of a stream of bullets. Many phenomena bear out these remarks, but only two will be considered in any detail as bringing out the point most clearly, viz. the photoelectric effect and the Compton effect.

The Photoelectric Effect.

It is found that if light falls on certain metals, for example sodium and potassium, the metal surface gives off electrons. The conditions of this emission of electrons by the metal have several characteristics quite foreign to light waves, and almost imperatively call for particles of light, or *photons*. The electron emission is studied by catching the electrons on a metal grid placed above the surface examined, and measuring the current, due to the flow of electrons, which passes; the energy of the electrons when they come out, or their speed of ejection, can be measured by determining the electric potential which is required to stop them.

Careful measurements have demonstrated the following facts:

1. The energy of the ejected electrons is quite independent of the intensity of the incident beam. If the lamp or source of light is made stronger, this has no effect on the energy of the ejected electrons—it merely increases the number.

2. The electrons come out immediately the light is switched on (if they come out at all, see below). There is no time-lag such as would be needed to absorb energy.

Remembering these two results, let us consider the wave picture. The stronger the light, the more energy available. This is turned to use, however, *not* by the electrons coming out with greater energy; they come out with the same energy, but *more* of them come out. If the beam were very weak we should expect the electrons to trickle out; not a bit of it—they come out as fast but not in such numbers as before. They might be released by a sort of trigger mechanism, drinking up energy from the wave until they have sufficient to come out with the observed energy; but then there is no time-lag, so the suggestion is ruled out; moreover, the energy of the electrons is quite independent of the area of the metal (over which the electrons might conceivably "drink up energy") and its distance from the source. In fact:

3. The only thing that does affect the energy of the ejected electrons is the colour of the light used, that is to say, the wave-length. The shorter the wave-length, the faster the electrons come out, and if the wave-length be longer than a certain value no electrons are emitted at all. If E = energy of the ejected electrons, ν the frequency of the light used, then it is found experimentally that

$$\frac{E + W}{\nu} = \text{Constant},$$

whatever metal is used, W being a constant characteristic of the metal.

The constant occurring on the right-hand side of the above equation was found to have precisely the same value as a quantity h, known as Planck's constant, which occurs widely in atomic phenomena (see p. 36). In order to derive a formula agreeing with experiment for the emission of radiation from hot bodies, Planck had found it necessary to suppose that energy was transferred from matter to radiation in units or *quanta*, each unit or *quantum* being proportional to the frequency ν, so that energy was emitted in multiples of $h\nu$. The new result just mentioned implies that in the reverse process, where energy is given up by radiation to matter, the transfer again takes place in quanta.

To explain the photoelectric effect Einstein put forward the bold theory that the energy of light is carried by *particles* (photons), the energy (E) of a particle being given by the equation $E = h\nu$. Thus, if we write the above equation in the form $E = h\nu - W$, we can state the result in words in the form: energy of ejected electron = energy light particle gives up — quantity dependent on substance, i.e. the work the electron must do to get out.

The Compton Effect.

This has to do with the passage of γ-rays of very short wave-length, that is very penetrating γ-rays, through matter

(cf. fig. 4, p. 20). Compton found that electrons were ejected from the material traversed, and at the same time another radiation of somewhat longer wave-length appeared. The phenomenon was quite incapable of explanation on a wave hypothesis. He proceeded to apply a particle argument. All the evidence of atomic phenomena, the line spectra of gases, X-ray line spectra, radiation theory (see *The Nature of the*

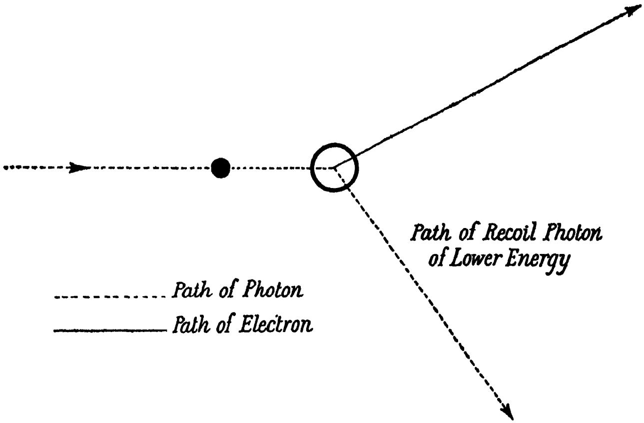


Fig. 13.—Compton's Experiment

The incident photon hitting the electron gives up part of its energy to the electron and recoils with corresponding lower energy. (This process has actually been photographed in an instrument known as a Wilson Cloud Chamber.)

Atom in this series) had previously indicated that a particle theory of radiation best fitted certain conditions. Compton took this theory and applied it to the subject in hand; his success provides one of the most striking examples of the success of the theory.

Compton considered the collision of two particles, a photon (or light quantum) and an electron. Simple mechanics showed that the electron would move off with a certain deduced velocity, while a photon recoiled with an energy lower than that of the incident photon; and, according to the equation

($E = h\nu$) of Planck and Bohr, lower energy is to be associated with longer wave-length and therefore weaker penetration. The experiments appeared to furnish direct evidence of collisions of billiard ball type between electrons and light particles (fig. 13), for the agreement between the theory and the results of experiment was striking.

I do not pretend to have given an exhaustive treatment of the experimental basis for a particle theory of light propagation. I have merely cited one or two instances which strongly suggest that we should look on the interaction of radiation and matter as a particle process. In point of fact, *all* questions involving interaction of radiation and matter demand a particle treatment, while we shall see that all questions of light distribution over extended areas demand a wave treatment.

We have said little about the vast evidence of atomic phenomena, the line spectra of gases, X-ray line spectra, and so on. The reasons why we consider the question of light in some detail are that it turned out that the impasse in which theories of *radiation* found themselves, namely, that radiation gave evidence of both a particle nature and a wave nature, was precisely what led to the new views of the constitution of *matter* which are our more immediate concern. For it was this dual nature of light which led Louis de Broglie to put forward his theory of matter waves, the wave-length of which he evaluated with the help of arguments in which he linked up quantum optics with wave optics in detail, as explained in the next chapter.

CHAPTER V

The Wave Nature of the Electron—I

Theory of de Broglie.

Historically there were two modes of approach to the wave theory of matter, that of de Broglie, and that of Heisenberg; we shall indicate in brief the salient features of only one of these methods of approach, that of de Broglie; and then proceed to discuss the *experimental* evidence for the wave nature of the electron. The Heisenberg approach is from quite a different angle, and does not lead directly to the picture of a wave structure. Possibly enough, the arguments which led to the conclusion that matter has a wave structure, may seem to the reader neither easy to follow nor convincing, but the subsequent experimental evidence is incontrovertible.

" Before Einstein, we were content with a purely wave theory of light and a purely corpuscular theory of matter. By his light quantum theory Einstein transferred the corpuscular concept of matter to light, and by combining this concept with the wave concept introduced a quite unexpected dualism or ' parallelism ' into the theory of light. Twenty years after this first step was made in combining the theories of light and matter, or of optics and mechanics, the French physicist, Louis de Broglie, made the second step—the ' complementary ' step as it were—in the opposite direction. He applied the wave conception of light to matter. In this way there arose in January, 1924—for the first time in the history of physics—the idea of ' material waves ' which are connected with moving particles of matter." (Frenkel.) *

To account for the experimental results, it had been found

* Frenkel, *Elementary Wave Mechanics* (O.U.P.)

necessary to attribute two contradictory properties to light, a wave nature from interference and diffraction results, and a particle structure from such phenomena as the photoelectric effect. De Broglie set himself the problem of reconciling these two aspects of light propagation, and of obtaining quantitative agreement between them. Qualitative results, results which were merely a question of whether such and such happened at all, whether, for example, an electron was ejected from a metal by photoelectric impact, were adequately treated by a theory of particle propagation. But wherever intensity questions were involved, it was found necessary to call in a wave mechanism.

It appeared from this dual nature of light that associated with a wave train was a stream of light particles (photons) which might be considered to travel along the rays. The number of photons which fell on a screen was to be measured by the intensity of the wave, which is measured by the square of the amplitude. Consequently the intensity of the wave at any point could be regarded as a measure of the probability that photons would arrive there; the diffraction patterns were pictures of the density of photons or light particles. Difficulties appeared, however, if we tried to localize the waves, or tried to associate a system of waves with each photon.

We have already stated that relativity theory predicts, and experiment bears out, a variation of mass with velocity; as the velocity increases, so does the mass, slowly at first but more quickly the nearer the velocity approximates to that of light. Indeed, relativity maintains that no form of energy can be transmitted with a velocity greater than that of light, and that to induce a particle, whose " mass " is not zero, to move with the velocity of light requires an infinite amount of energy. Now the wave particles do move with the velocity of light, hence we must conclude that their mass is zero. Is it unnatural to expect that if particles of zero mass, photons, have an associated wave mechanism, particles whose mass is not zero might also have an associated wave mechanism?

It appeared that, from Einstein's explanation of the photo electric effect, the energy of the wave particles was given by the Planck equation $E = h\nu$ where ν is the frequency of the light wave. It may be noted that this energy, the particle energy, was to be measured by doing a purely wave experiment which gave a determination of the wave-length λ, and then using the relationship $\lambda\nu = c$, where c is the velocity of light.

Now it has been known for a long while that, besides having energy, light has also momentum, since it can exercise a pressure; and that the energy and momentum are related to one another by the equation

$$\text{Energy} = \text{Momentum} \times c.$$

If, then, $E = h\nu$, it follows that the momentum (p) is equal to $h\nu/c$, i.e. to h/λ.

We therefore have two equations for light, viz.

$$E = h\nu, \text{ and } p = h/\lambda.$$

If T is the period corresponding to the frequency ν, we may write these as

$$ET = h, \text{ and } p\lambda = h.$$

These equations fit in beautifully with the theory of relativity; for in this theory length (λ) and time (T) are in a certain sense interchangeable, and so also are energy (E) and momentum (p). Moreover, according to relativity, if two observers are in uniform relative motion and wish to compare their observations, the equations connecting the values they find for momentum and energy are precisely similar to the equations connecting length and time.

So far, the discussion has referred to light only, so that the mass of the particles concerned, viz. photons, is zero. But de Broglie went on to generalize the idea, so as to make it refer to particles of mass not zero. It was difficult to understand, why, if the argument was correct for the one, for which

it had a sure experimental basis, it should not be true for the other, although hitherto no evidence of a wave-like structure for particles had been observed.

It was possible that the physical constant h which appeared in the equations might have a different numerical value in the two cases of photons and ordinary particles—this could only be checked by experiment—but it appeared that all matter ought to have an associated wave-like structure, the wave-length being given by

$$\lambda = \frac{h}{\text{momentum}} = \frac{h}{mv};$$

for a particle of mass m, moving with velocity v (considerably less than that of light) has a momentum mv. Now for the case $m = 1$ gm. and $v = 1$ cm./sec.),the formula gives $\lambda = h$, that is of the order of 6×10^{-27} cm., a value wildly beyond the possibility of experimental verification; the wave structure of ordinary matter simply cannot be demonstrated, the wave-length is far too short. To bring the associated wave-length within the region of possible observation it is necessary to use small particles moving fairly slowly. The lightest known particle is an electron, the mass of which is 9×10^{-28} gm., so that, for this particle,

$$\lambda = \frac{h}{mv} = \frac{6 \times 10^{-27}}{9 \times 10^{-28} v} = \frac{60}{9v}.$$

An electron which has fallen through a potential difference of 1 volt has a velocity of about 10^8 cm./sec. ($\frac{1}{2}mv^2 = Ve$), so that $\lambda = \frac{60}{9 \times 10^8}$, say 10^{-7} cm., which is of the same order of wave-length as the long waves of X-rays, and is quite capable of observation.

With regard to the nature of these waves associated with matter, some difficulty arises. It appeared that the velocity of the wave—sometimes called the phase velocity—was

greater than that of light, the expression for the wave velocity being $\frac{c^2}{v}$, where c is the velocity of light and v is the velocity of the particles.* For the case, then, of particles of mass greater than zero the wave velocity must always be greater than c. It can be shown, however, that the velocity of a *group* of such waves (see p. 27), associated with electrons, is precisely the velocity of the *electrons* themselves. In other words, the wave group moves on at the same speed as the particle. As we have already mentioned, the theory of relativity asserts that energy cannot be propagated with a velocity greater than that of light, but this leads to no inconsistency, for the energy propagation is associated with the motion of the electrons, and these move with the *group* velocity. The phase waves are merely of the nature of control waves and carry no energy.

We shall return in the last chapter to the problem of the nature of the waves. The important feature at present is that matter ought to give evidence of a wave structure. Let us turn to experiment for verification; are any of the well-known wave patterns found associated with matter?

The Experimental Evidence.

We have seen that the regular structure of crystals made it possible to obtain conclusive evidence of the wave nature of X-rays, since the spacing of the atoms in a crystal is of suitable dimensions to give a characteristic wave pattern with X-rays. The experiments with electrons were similar.

We have talked of "beams of electrons of velocity v";

* The relativity expressions for the energy (E) and momentum (p) of a particle of rest mass m_0 moving with velocity v are

$$E = \frac{m_0c^2}{\sqrt{(1 - v^2/c^2)}}, \quad p = \frac{m_0v}{\sqrt{(1 - v^2/c^2)}}.$$

Since $E = h\nu$ and $p = h/\lambda$, it follows that the phase velocity of the waves (viz. $\lambda\nu$) is given by $\lambda\nu = E/p$. But the first two equations give $E/p = c^2/v$. Hence the phase velocity is c^2/v, and this is greater than c, since the particle velocity v is always less than c. The relation, wave velocity $= c^2/v$ is quite general. Photons have a velocity of c, so that the wave velocity of light (c^2/c) is also c.

the experimental realization of such beams is a matter of some intricacy. As is usual, the simplifications which the theorist introduces are precisely the simplifications the practical man has difficulty in realizing. To obtain a beam of electrons is a simple matter; the difficulty lies in sorting them out until we have a beam in which all the electrons have the same velocity. All electron diffraction apparatus consist of three parts:

1. A source of electrons.
2. A means of selecting electrons all of known velocity.
3. The crystal spectrometer, that is the crystal with its associated mechanism to show the wave structure.

The source of electrons may be a cathode ray tube—the reader will remember that the electron was discovered in experiments with a cathode ray tube—or a hot filament of wire from which the electrons are, so to speak, boiled off. They may be accelerated in a vacuum by an electric field. A vacuum is necessary, since if any gas is present the electrons bump into the atoms of the gas and lose their energy—as in the experiments of Franck and Hertz. The electrons, now of known velocity, fall on a crystal and are subsequently collected. It is the manner in which they come off the crystal that is important; they show the simple patterns we associate with waves.

The earliest *conclusive* evidence of the wave nature of the electron was obtained by Davisson and Germer in America in 1928. Certain anomalies appeared in connexion with the reflection of electrons by crystals. Elsasser was the first to draw attention to the bearing of the wave hypothesis on these results. There was evidence that electrons were strongly reflected at certain angles, in a manner which admitted of explanation only on the hypothesis of a wave mechanism. Analysis of the results led to complications, but it appeared certain that crystals affected electron beams in much the same way as X-ray beams. Indeed, electron beams are more useful in the study of the surfaces of crystals than X-rays,

since the latter penetrate while the former are more readily absorbed, a fact which has rapidly led to technical applications. Because of its complexities we shall not discuss the method of Davisson and Germer, but pass on to the experiments of G. P. Thomson, made about the same time, since these demonstrate very clearly the relationship of beams of electrons with beams of X-rays. Similar patterns are obtained in the two cases (cf. Frontispiece).

In broad outline the method of Thomson was to pass a narrow beam of electrons through a very thin crystalline film;

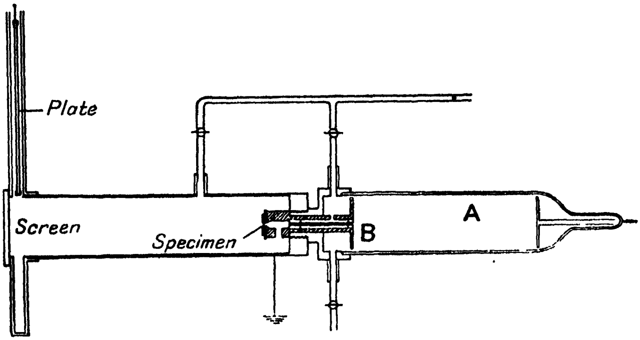


Fig. 14.—G. P. Thomson's Early Apparatus
(From *~~Electric~~ Diffraction*, by Beeching: Methuen)
electron

the electrons of the beam were diffracted in their passage through the film and formed a circular pattern on a photographic screen behind the film. The apparatus is shown diagrammatically in fig. 14. The electron beam is produced in the manner in which electrons were first discovered, in a discharge tube A, at the cathode, which in the diagram is the right-hand terminal. They are accelerated by the applied voltage, of the order of tens of thousands of volts, and pass through the thin tube B, which defines the width of the beam. Across the mouth of the tube is placed the very thin metal film through which they pass to the photographic plate. The apparatus is of course highly evacuated to prevent the

bumping of the electrons into atoms of the gas which would otherwise take place.

The method is exactly analogous to a method of X-ray analysis known as the Debye-Scherrer or Hull method, which we must now consider.

A crystal consists of a regular array of atoms, which may be situated, for example, at the corners of cubes, as is the case

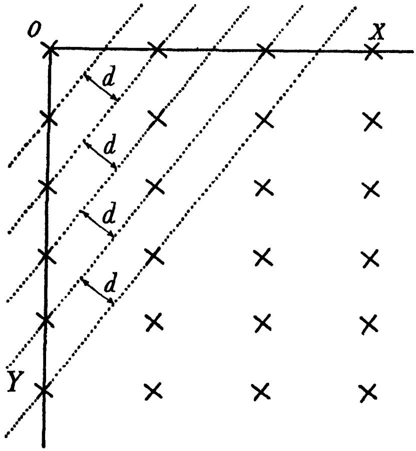


Fig. 15.—Dotted lines show a layer of crystal "planes"

in crystals of salt, or in many other arrays, the significant fact being that in any crystal the atoms are regularly spaced, and can be arranged in parallel planes or layers, each layer of atoms in itself forming a regular array (fig. 15).

The radiation is reflected by the atoms in these layers, or planes, when the angle of reflection bears a certain relation to the spacing between parallel planes or parallel layers of atoms. This relation is a consequence of the fact that the waves reflected from successive parallel layers must be in phase, so that they may reinforce each other in order to give a strong reflected beam. Expressed as a formula the relation is

$$p\lambda = 2d \sin \theta,$$

where λ is the wave-length, d the distance between the planes, θ the glancing angle of reflection or Bragg angle, and p any whole number. So long as we are dealing with a specific crystal, d is given, and the formula gives the possible values of θ corresponding to a definite wave-length.

So much for a simple crystal. A metal is a conglomeration of small crystals arranged at random. What diffraction effect, if any, can be observed by using a "powder of crystals"?

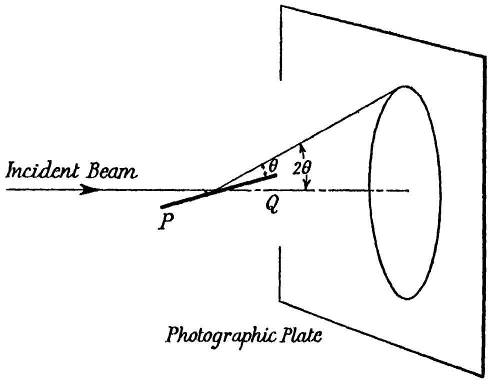


Fig. 16

In a powder the crystals are arranged at random, so there are always a certain number inclined at a given angle to the incident beam; if for any plane of atoms this angle be taken as the Bragg angle, the angle θ above, then there will always be a certain number of crystals so arranged that Bragg diffraction will take place.

In fig. 16 PQ is the crystal plane and θ the Bragg angle. The angle the beam is turned through when it is reflected, is 2θ. So long as the angle between the reflected beam and the incident beam is 2θ, there are always crystals correctly placed to diffract. The diagram is a section, and the complete picture is obtained by turning the whole figure about the direction

of the incident beam as axis; in fact, we get a cone of reflections from planes of the type PQ. If now we put a photographic plate at right angles to the axis of this cone, i.e. to the direction of the incident beam, the X-rays will affect the plate all round a circle. Since in a crystal there are many such planes of atoms, separated by distances d, d', d''..., and consequently different Bragg angles θ, so we get several reflected cones for each given wave-length, and on our photographic plate several concentric circles.

Let us turn specifically to the case of electrons.* In G. P. Thomson's experiments, the electron beam generated in a discharge tube A (fig. 14), passed through a defining metal canal B, and fell on a very thin foil of metal. The photographic plate showed the series of concentric rings which were expected. That it was undoubtedly a case of diffraction of the electrons themselves was proved by the fact that a magnet brought near the beam shifted the whole pattern of concentric circles; only streams of charged particles are affected by a magnetic field. Unfortunately, metals absorb electrons very readily so that the experiment can only be performed with fast electrons and very thin metal films (of the order of 10^{-5} cm. thick). An electron diffraction photograph for gold is shown in the frontispiece, and may be compared with that obtained for quartz with X-rays. It will be seen that the two photographs are in every way similar.

We have then direct experimental evidence of the wave nature of the electron. The above method, here treated in detail, is but one of many which have been devised to test the wave hypothesis of de Broglie. In particular, Rupp has succeeded in diffracting electrons by means of a ruled grating used at grazing incidence. As the result of all these experiments, de Broglie's theory has been amply verified. Not only has his wave hypothesis been supported qualitatively, but the value of the wave-length predicted by de Broglie (viz. $\lambda=h/mv$) agrees with the experimental value, that is to say, the value

obtained from the diameter of the rings and a knowledge of the crystal spacing.

The theory of de Broglie leads to the conclusion that all matter has a wave structure—that electrons are not unique in this respect. This has been borne out by experiment. Not electrons only show a wave structure, but also atoms and molecules. The wave structure shown is essentially associated with matter; the waves are matter waves, not electricity waves.

CHAPTER VI

The New Mechanics

The electron first came before us as the smallest particle in the universe, a constituent of all matter, carrying the fundamental unit of charge. It was pictured as the smallest, hard particle, the ultimate in billiard balls. It is true that to attach to it a precise and definite radius, an exact size, was a matter of some difficulty. The radius could not be measured directly and was a theoretical deduction. The billiard ball picture is inadequate.

In the preceding chapter we have considered some of the evidence which led us to conclude that the electron was associated with some kind of wave system. In the experiments cited all the evidence was obtained with *streams* of electrons, and the results indicated that streams of electrons showed properties associated with waves, that the intensity at any point appeared to be controlled by some sort of wave mechanism, for the intensity distribution showed the regular pattern associated with wave propagation. Streams of electrons then behave under certain circumstances like waves. It is manifest that this result is bound to affect our picture of the electron itself, the picture of the small particle. The intensity of a beam of a large number of electrons is a simple concept—it is given by the relative numbers; but if we imagine our beam limited to one electron, the wave pattern is unaltered, it depends solely on constants like the wavelength of the associated wave system, which in turn depends on the velocity of the electrons and is independent of their number. On the other hand, what can an intensity pattern

for a single electron mean? As a particle, we cannot imagine it to have a broad space distribution like a wave pattern, and yet it appears we must allow it to have such a pattern.

A way of resolving the difficulty, suggested by Professor Born, is to use the idea of a " probability pattern ". The pattern for a single electron is not to be looked on as an intensity distribution in the ordinary sense of the word, but a pattern describing the probability or likelihood of the electron arriving at any point; the greater the pattern density, the more likely that the electron will arrive there. The idea in its application to electrons is completely new, and indeed foreign to our normal or classical modes of thought; we shall consider it at greater length in the next chapter. That something new and at first sight strange should appear is not surprising. After all, the electron is one of the ultimate constituents of the universe, one of the fundamental bricks, and it is not surprising that the ideas and methods of treatment derived for ordinary matter, for vast aggregates of electrons, should require modification when we come to consider the electron itself. The ordinary mechanics, or calculus for investigating the motion of bodies, assumes that if we know at any instant the position and momentum of every body, we can, from the laws of motion, derive completely the subsequent movement. In this argument the conclusion may be correct, but what about the hypothesis? Can we in actual fact always claim to be able to find out the precise position and momentum of an electron?

The new evidence of the wave nature of the electron thus raises difficulties, which we shall consider in the last chapter; nevertheless certain facts emerge independent of these difficulties. A wave form of description appears necessary; this follows directly from the experimental evidence and from the properties which a wave possesses simply because of its waviness, irrespective of the nature of the wave or of what we consider to be vibrating.

De Broglie gave theoretical reasons for believing that a

particle has a wave structure, and obtained the relationship between one of the defining constants of a wave motion, viz. the wave-length, and the velocity of the particle considered. His investigation referred, in the first place at least, to a rather limited class of electrons, those moving with constant velocity. Schrödinger generalized his ideas. A wave motion has its own characteristic system of equations or properties; Schrödinger demonstrated how these could be set up in the correct form appropriate to the motion of electrons. His method was to obtain, by analogy from geometrical and physical optics, a calculus which enabled him to transform the well-known particle equations to the corresponding equations of the wave motion, to transform classical mechanics into wave mechanics. By this means he set up what is now referred to as Schrödinger's equation, a mathematical description of a wave motion by means of which we can deduce the wave pattern of an electron under different circumstances.

This wave equation calculus when applied to an electron which is moving in the electrical field of a nucleus (cf. *The Nature of the Atom*) leads to the conclusion that the electron can only have certain discrete energies. In fact, the electron energy appears as a term in Schrödinger's equation, and it is only when this energy has one of a certain series of values that the equation has a physically intelligible solution at all. Thus in the electric field of a nucleus the electrons must separate out into energy levels, whose values, as determined by Schrödinger, agree with those of the Bohr model, in which they were obtained by somewhat arbitrary assumptions.

Direct experimental evidence that the electrons constituting an atom are separated out in discrete levels has long been known. We can see in a rough pictorial way that this must be so. If we attach a wave-structure of wave-length λ to an electron which on a particle picture we imagine moves round the nucleus in a circle of radius r, then the complete path round the nucleus, $2\pi r$, must be an integral number of wave-lengths, otherwise the electron wave will interfere with

itself. This is simply the argument that if waves are to reinforce, and are not to annul one another, they must be in phase (cf. p. 29). If they are in phase, a stationary wave is established. This argument leads to the conclusion that $2\pi r = p\lambda$, where p may be any integer. But $\lambda = \frac{h}{mv}$, the de Broglie relation which Schrödinger generalized; therefore $2\pi r = \frac{ph}{mv}$, and a little algebra demonstrates that this is precisely equivalent to the assumption from which Bohr deduced the energy levels or stationary states.

The new point of view is then that if we wish to study the properties of the electron under certain circumstances, we must study the properties of a particular type of wave motion and forget our picture of the electron as a particle. It must not be thought that the picture of the electron as a particle is wrong; it is inadequate or incomplete. The wave picture and the particle picture are not contradictory, but complementary, as in the case of light. Just as with free electrons, so when we consider the properties of electrons at home in atoms, we find that some sort of wave picture is necessary. We shall see in the next chapter that this is not so very surprising.

The successes of the new wave mechanics, the new outlook on the electron, have been many. In certain cases, it is true, the mathematical analysis has proved cumbersome, but the results have been entirely satisfactory. The firmest evidence in support of any theory is that experiment bears out the logical consequences of that theory; that in its simple form it covers a wide field, uniting what was previously disjointed, demonstrating relationships which were unsuspected. The new mechanics has been eminently successful in this respect, and from it we have obtained a clear picture of many phenomena which hitherto appeared recalcitrant and isolated. The Bohr picture has been clarified and extended; it appears that the physical significance of a quantum number is to be found

in the number of nodes of the stationary wave system which describes the behaviour of the electron in the atom. The anomalies of spectra have been largely cleared up; Dirac has shown that the existence of electron spin can be deduced by considering the effect of certain conditions laid down by Special Relativity. The difficulties of molecular structure are yielding to the wave treatment, and a plausible picture is obtained of metallic conduction. The successes are legion—it is of little moment even to try to enumerate them in detail. The technical reader is referred to the bibliography; the layman will appreciate that the new theory has received ample confirmation and been a source of most fruitful investigation.

CHAPTER VII

The Wave Nature of the Electron—II

In the previous chapters we have discussed the wave properties of electrons; we have considered some of the experimental evidence that electrons have wave properties; we have pointed out that the association of such properties with electrons has cleared up many problems and afforded a line of very fruitful investigation. Nothing has been said of the nature of the waves, of the real " wave nature " of the electron. That, after all, this is not the crux of the question, as might at first sight be expected, has, we hope, been made clear. Yet it is manifest that some answer to the question inherent in the title must be attempted. We have in this chapter to discuss two things, first the dual rôle of wave and particle played by the electron, and secondly the nature of electron waves.

It appears that light also plays this dual rôle of particle and wave: when we experiment or play with light, we catch it and throw it as we catch and throw a ball, but, in flight, its motion is controlled by waves. When we conduct refined experiments on matter and play with the ultimate in particles, we find the same features; we catch them and throw them as particles, yet their motion is characterized by waves. Let us consider again carefully the argument on which this conclusion is based.

By a particle surely we understand a small body of definite size which at any definite instant of time has some definite position, that is, occupies some specific portion of space. But how does one determine the size, and the position, of an

electron? The two problems are allied, for if we determine the position as lying within certain limits, we may consider the difference between these limits as affording a rough idea of the size of the particle.

Now a screen placed to intercept a beam of not very small particles casts a geometric shadow; if we direct the beam on to a slit, then the narrower the slit, the narrower the beam of particles on the other side, until when the slit becomes slightly smaller than the size of the particles, no particle gets through to the other side. If, however, we try to obtain some idea of the size of an electron by this means, we find that so long as the slit is wide, say a few millimetres in breadth, it remains true that the narrower the slit, the narrower the beam getting through; but a stage is reached when on narrowing the slit still farther, the beam becomes broader; we can study the breadth of the beam by stopping the electrons on a photographic plate. It is true that the slit is now very narrow indeed, and it is necessary to have recourse to rather complicated means to obtain suitably narrow slits; but the broadening, which is accompanied by the pattern structure we associate with wave diffraction, appears while the slit is still much broader than the electron, according to the rough ideas we can form from other evidence. Slits or what is effectively the same, grating spacings of the order of 10^{-8} cm. are required.

Now the electron particle, as we picture it, is very decidedly smaller than an atom of which it is a constituent, and the diameter of an atom is roughly of the order of 10^{-8} cm. In fact, the pure particle picture of the electron, which we are engaged in showing is incomplete, leads to the conclusion that the size of the electron is of the order of 10^{-13} cm. or about 1/100,000 of the breadth of the slit. Such a figure for the size of the electron is of course a theoretical deduction which rests on certain assumptions as to the nature of the electron's mass. That it is not borne out by experiment, is what we are engaged in pointing out.

If we pass the electron beam through two of these narrow

slits simultaneously, that is, if we set up two parallel narrow slits perpendicular to the beam, and consider what happens in this case, the evidence is even more startling. Surely our particle goes through either one slit or the other. Yet the wave pattern characteristic of two slits is formed at the other side; in other words, where the electron is to go is decided by the fact that there are two slits. It is quite hopeless to devise a particle which can be in two places at once, which can go through two slits at the same time. The control mechanism which decides where the electron is to go must extend over both slits, like a system of waves spreading out through space.

It must not be thought that the difficulty can be got over by assuming that the electron has a complex structure, that it is a broad particle which really does extend over the breadth of the two slits, and that part goes through one slit, part through the other, and part is left behind. The electrons which get through have the normal charge and mass, and are in every way identical with electrons which have not passed through two slits. Alternatively it might be thought that the pattern was due to some form of interaction between the electrons, that an electron which had gone through slit A might interact with an electron which had gone through slit B, in some way which resulted in the wave pattern distribution observed; in such a case the type of pattern obtained would depend on the number of electrons passing through, which it does not. The only factors which affect the pattern are the dimensions and separation of the slits and the velocity of the electrons, and these enter into the result in a manner only consistent with the assumption that the slits diffract a train of waves, the wave-length of which is given by the de Broglie relation $\lambda = \frac{h}{mv}$.

In asking the question "what is the nature of those waves?" we really want to know "what is it that vibrates?" We find that the propagation of sound shows the characteristics of wave motion; moreover, we can detect the air vibrating, and

when the air is removed we hear no sound; hence we say that it is the air that vibrates. When we set up waves on a sheet of water, we say they are water waves because we can detect the water vibrating. When it was discovered that light showed wave properties it was natural to wonder what was vibrating—or what the medium was through which the waves were propagated. Various experiments were designed for the purpose of detecting the presence of this medium, but all of them gave negative results, so that the "ether", as it was christened, remained a theoretical concept. The emphasis has now been diverted from the theoretical properties of a hypothetical medium, and is transferred to the observed properties of the wave motion. So it is with matter waves also. To the question, "what is it that vibrates?" no specific answer can be given.

If, however, the question be regarded from a slightly different point of view, a clearer appreciation of the significance of the experimental results may be obtained. Consider again the two slits on which a beam of electrons falls. The wave pattern obtained gives a picture of the distribution of the electrons which reach the observing screen. Now the type, shape and form of the pattern, which can be deduced from the wave hypothesis, is quite independent of the number of electrons which fall on the slits; this number certainly determines the absolute density at any point, but not the relative density at different points. The denser the pattern at any point, the greater the number of electrons which arrive at that point: at certain other points no electrons at all arrive, a fact which is brought out in the pattern. For electrons setting out on their voyage across the slits, the wave pattern gives an idea of where they are likely to arrive; most of them will arrive where the pattern is most dense, fewer where it is tenuous. For any individual electron the pattern is a picture of the various places it may land, and the likelihood of its reaching them.

It may be argued that the electron can only land in one

place and that something better than a picture of where " it is likely to land " can be obtained; but the knowledge that any specific electron can land in only one place is of no help whatsoever in our effort to predict where that place will be. The wave pattern then is a picture of " likely places of arrival of electrons ". Perhaps this is made clearer by considering the electron beam to be limited to one electron: the wave pattern is unchanged, the pattern gives a picture of probable places of arrival of the electron; in one experiment, it might arrive at one place; in another experiment, at a different place. From the associated wave mechanism the wave pattern can be constructed and the probable places of arrival mapped out; indeed, this is the whole function of the wave theory, to map out the probable places of arrival and attach a " likelihood of arrival " to each point in such a map. This is all we mean when we describe the waves as " waves of probability ".

When we set out to delimit the electron in a direction perpendicular to its motion by means of slits and the like, we came to the conclusion that the electron in flight was best described by a train of waves. The next question which occurs to one is: " where in the train of waves are we to look for the electron?" This question really confuses the issue; nothing has indicated that the electron is a particle and a wave; an electron is an electron. To follow its career, at times we must picture it as a particle, at other times as a wave; at no instant does it exhibit both properties. *Where* it will land is controlled by a wave mechanism; *when* it lands, it lands as a particle. The question, however, is worth a little further consideration. To describe the motion of an electron, we require a group of waves: now it was pointed out (p. 28) that the velocity of a group of waves is not necessarily the same as that of the individual waves (the phase velocity), and here the interesting fact emerges that the group velocity is precisely the velocity calculated in the ordinary way by treating the electron as a charged particle. This indeed must

be so if the motion of the group is in any sense to describe the motion of the electron. It is certainly difficult in tracing the career of an electron to picture it first as a particle and then moving across space as a group of waves; we may say, however, that the particle is " somewhere in the wave group."

It seems then that in whatever direction we try to delimit the electron, it evades us; as we snatch at it, it slips through our fingers not so much like an eel, but rather as if we were snatching at a thin cloud.

We pass on to consider another idea, which has recently become of very great importance, and which throws a vivid light on what we are trying to do, and what degree of success we may hope to achieve. When we set out to measure any quantity, we try not to alter it in any way; we try to arrange matters so that the process of measurement will not affect the thing we are trying to measure. For instance, obtaining the speed of a runner by timing him with a stop-watch obviously does not affect his running. On the other hand, one conceivable way—certainly not a good way—to measure the velocity of a shell would be to allow it to hit a movable target, and then to observe the motion of the target; in this case we would destroy the velocity by measuring it. We may then divide methods of measurement into two broad classes: (1) those which do not appear to modify the quantity we set out to measure; (2) those whose avowed object is to modify or even destroy the quantity to be measured, the known and controlled causes of the observed modification enabling us to deduce the unmodified value which we seek.

When we conduct experiments on bodies of normal size, the bodies of everyday life such as runners and shells, it is comparatively easy to devise them so that the process of measurement does not radically influence the property we wish to observe. As we reduce the size of the objects employed, greater ingenuity is required; the question then arises, can the reduction of size be carried on indefinitely? When we reach a stage when we are defeated in our efforts, is our defeat

simply due to lack of ingenuity? And to what extent can we get round the difficulty by the second method of measurement, by working back from the observed modification to the original state of affairs? What happens when we experiment with the ultimate in particles such as the electron?

Now our knowledge of the existence and properties of the electron is derived from experiments using vast numbers of electrons. As it is both the smallest particle and a constituent of all matter, an experiment, which is merely an arranged set of conditions under which we induce the electrons to do certain things, is very much a case of using a sledge-hammer to move a walnut. It is true that we may deduce what will happen from our knowledge of the laws that control the experiment, but our knowledge of the laws which control sledge-hammers is derived from our experience of using them to drive in piles and the effects in the two cases may be of altogether different types, and obey quite different laws.

We have spoken of a certain class of experiments which " do not affect the quantity to be measured ", as opposed to others which modify it considerably. Now while this distinction is clear enough when we are dealing with the ordinary bodies we can observe every day, it is a little misleading when we come to experiment with the smallest particle at our disposal. A measurement is of the nature of a confession wrung out of the system measured. It is not sufficient if the apparatus provides the circumstances in which we wish to study the system, it must also provide a means whereby the system will be made to show the change or property we set out to measure. The difficulty lies in the fact that the system, while placed in a set of accurately known and isolated circumstances, must interact with these circumstances in some manner which enables us to obtain our measurement. And of course, in producing this measurable effect on the circumstances there is the accompanying reaction of the circumstances on the system we are measuring, which is thus changed to a greater or less degree. We have no direct means of esti-

mating the degree of this change, we can only conduct other experiments, with their accompanying reaction, and, provided no inconsistencies appear, the picture must be considered satisfactory.

At present, however, we *are* faced with something of the nature of an inconsistency, viz. the dual aspect of the electron. Here the trouble appears to be much more fundamental than mere lack of ingenuity. Bad technique merely gives values for the quantity measured which are not reproducible. A measure of the accuracy of a technique is given by the extent to which various determinations of the same quantity agree among themselves, i.e. by their consistency. The difficulty before us is a systematic inconsistency, two quite different types of behaviour, each by itself quite definite and clear, which give two apparently independent pictures of the electron. The question we are raising now, in fact, is not: how much *do* we know of the electron, but how much *can* we know of it?

"All measurement involves the paradox that the system measured must be at the same time an isolated whole and a part interacting with other parts. Measurement is impossible unless the system acts upon the apparatus of observation, and the measurements are meaningless unless the system retains its identity and characteristics." *

An electron is a deduced entity. It is not proposed here to enter into a discussion of theories of knowledge and discuss such matters as what is meant by saying that an electron, or anything else, *really* exists. Problems such as the one that we are considering at the moment have stimulated scientific interest in such philosophic matters. Our concern at the moment is with the purely scientific. We are interested primarily in a scientific picture. Our models or mental images are built to correspond with our experimental results; but we must take care not to allow ourselves to be carried away by our models. If the knowledge which we can obtain from

* Temple, *The General Principles of the Quantum Theory*, (Methuen).

experiment is limited—and in a moment we shall try to snow more clearly that such knowledge has inherent limitations—then it is idle to attach to these models, by analogy or otherwise, properties which we cannot observe. It is " natural " to expect a particle to have certain properties, and by " natural " we simply mean that the large scale particles of everyday life have these properties. But we are not interested in the investigation of properties of particles but, we repeat once more, in the properties of electrons.

The fact that the electron appears to be one of the ultimate components of the universe, one of the fundamental bricks from which, and of which, all matter is composed, places certain limitations to the accuracy with which we can control its behaviour, and it is only from controlled behaviour that we can deduce properties. Of course, should we find that the electron has a complex structure providing us with still smaller tools, then such speculation must be pushed one stage farther. Its relevance will not then bear on electron behaviour, but on that of the still smaller entities. But even if such a state of affairs were to arise, giving a situation very similar to that which arose when it was discovered that the atom had a complex structure, we should merely have pushed the frontier one stage farther back. At the present moment the electron seems to be, and seems likely to remain, one of the ultimate entities of the universe.

In discussing the question of how much we may hope to learn of electrons, or " how much we *can* know of the electron ", it is manifest that we need only consider the most refined tools at our disposal. Coarser weapons merely make matters worse. And the most refined tools at our disposal are other electrons, and light corpuscles (photons). These are the two minutest entities we can use, and will give us the highest accuracy.

Before we can discuss the motion of a particle with precision, we must know at some stage in its career two things about it, its position and its velocity. Now one of the most

astonishing facts, or ideas, that have emerged from the new developments in physics is just this, that exact knowledge of *both* these two things simply cannot be had—it is impossible. If we so desire we may determine one or other of the two things—the position and the velocity of a particle—with any accuracy we require, but only at the expense of knowledge of the other.

No doubt there is a sense in which all scientific knowledge is only approximate, never exact. But an inherent and definite bar to our knowledge, such as we are now speaking of, is another matter.

By refining our technique indefinitely, we may in theory determine as exactly as we please *either* the position *or* the velocity of a particle; but no refinement of technique will ever enable us to determine *both* at the same time with arbitrary accuracy.

It appears that the errors in the simultaneous determination of position and velocity obey a relationship of the type:

$$\text{(error in determination of position)} \\ \times \text{(error in determination of velocity)}$$

cannot be less than h/m, where m is the mass of the particle and h is our old friend Planck's constant. Now h is very small. If we use as the units of mass, length and time the gram, centimetre and second, h has the value $6{\cdot}56 \times 10^{-27}$ erg-sec., a number which is quite fantastically small: it is 6·56 divided by 1000 million million million millions: or 6·56 divided by 1 followed by 27 zeros.

The effect we are considering is of course absolutely beyond the reach of observation in ordinary life. But when we experiment with electrons, the limit to our accuracy becomes significant. For example, if we decide to determine the position correct to 1/100,000 cm. (about 1 wave-length of light), then, according to the above relation we could only determine the speed of a particle of mass 1 gm. correct to about

$\frac{6 \times 10^{-27}}{1} \times 10^{5}$ or 6×10^{-22} or 6 divided by 10,000 millior million million centimetres/sec.—which most people will agree is pretty accurate. We should indeed find it difficult to realize such an accuracy experimentally. On the other hand, if we take an electron which has a mass 9×10^{-28} gm. and again decide to determine the position correct to 1/100,000 cm., the error in determination of velocity becomes $\frac{6 \times 10^{-27} \times 100{,}000}{9 \times 10^{-28}}$, or $\frac{2}{3} \times 1{,}000{,}000$ cm./sec., or 6 kilometres per second!

A physical illustration may help to make this *Uncertainty Principle* clearer. Let us suppose that we wish as an ideal experiment to determine the position of a moving electron by examining it through a microscope. (The experiment cannot be realized in practice because the wave-length of the illuminating light must be much shorter than any visible to the human eye). Consider the electron when it is in such a position that the cone of rays scattered from it through the object glass of the microscope has an aperture α (fig. 17). If the illuminating light is of wave-length λ, then optical wave theory shows that the uncertainty in the determination of the position of the electron, Δx, is given by $\Delta x = \lambda/\sin\alpha$. (Hence we see why λ must be small.) This uncertainty Δx can only be cut down by working with a shorter wave-length λ.

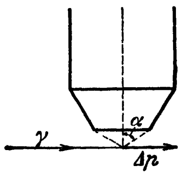


Fig. 17

The influence of the Compton effect must not be forgotten, however (see p. 43). We cannot ignore the result of photon collision with the electron, and for any measurement of the position of the electron to be possible at all at least one photon must be scattered by the electron. Detailed treatment of the Compton effect shows that from this collision with the photon the electron receives a recoil momentum (p) of the order of h/λ (momentum = mass × velocity). The direction of the

recoil cannot be determined exactly as the direction of the scattered photon may be anywhere within the cone. There is therefore an uncertainty (Δp) in the component momentum of the electron perpendicular to the axis of the microscope, given by the relation,

$$\Delta p \sim \frac{h}{\lambda} \sin \alpha,$$

(where the symbol $\sim$ means: " is of the same order of magnitude as "). Thus, after the experiment to determine the position of the electron has been made, we are left with an uncertainty in position determination given by $\Delta x = \frac{\lambda}{\sin\alpha}$ and an uncertainty in momentum given by the above relation. Hence it appears that

$$\Delta x \, \Delta p \sim h \quad \text{or} \quad \Delta x \, \Delta u \sim h/m;$$

we have therefore proved the uncertainty principle for this particular case.

The further development of the quantum theory has brought out the fact that there are other pairs of quantities, besides position and momentum, to which the uncertainty principle applies. Energy and time, for example, are two such quantities.

In the preceding pages we have considered the limitations inherent in a particle form of description and demonstrated how these lead us to infer a wave structure. We might equally well have shown how a wave group observed on the appropriate large scale exhibits particle properties. But although an electron appears to behave under certain circumstances as a particle and under certain other circumstances as a set of waves, yet there is no inconsistency. " Any real, that is, experimentally demonstrable, contradiction between wave theory and particle theory is impossible.*

At one point in the above discussion, we pointed out that

* Born, *The Restless Universe* (Blackie), p. 163.

care must be taken not to impute to our scientific models properties which cannot be verified by experiment. The whole problem of the behaviour of the ultimate particles of the universe has in fact been reconsidered carefully by Heisenberg and others from the point of view that no physical quantities may enter into the deductive argument which are not experimentally " observable ". This slightly different and more philosophic approach has led to the new Quantum Mechanics. The different approach leads precisely to the same conclusions as the more directly physical picture of waves.

Throughout the whole of the present book we have been occupied exclusively with electrons. But the uncertainty relations discussed are not a unique property of electrons—they are common to all particles. The wave nature is not peculiar to the electron. It is common to all matter. The waves are matter waves rather than electron waves.

BIBLIOGRAPHY

For a general discussion of the scientific approach to the study of nature, *The Nature of the Physical World* by Eddington (Everyman, 2*s.*) is excellent. *The Restless Universe* by Born (Blackie, 8*s.* 6*d.*) gives a more specific discussion of the problems and methods of Modern Physics. *The World in Modern Science* by Infeld (Gollancz, 5*s.*) is an attempt to cover the field embraced by both these books. The author would recommend perusal of all three of these books.

For the student who wishes to follow the subject still farther there is a host of technical books. *Quantum Mechanics* by Gurney (C.U.P., 8*s.* 6*d.*) gives in descriptive form the general conclusions of the Wave Theory of Matter. With regard to the particle electron the standard book is *The Electron* by Millikan (C.U.P., 10*s.*). (A new edition: *Electrons, Protons and Cosmic Rays* (15*s.*) has recently been published). *Atomic Physics* by Born (Blackie, 17*s.* 6*d.*) contains a lucid and up-to-date account of the physics of the atom, and of the various forms of the quantum theory. *Atomic Theory and the Description of Nature* by Bohr (C.U.P., 8*s.* 6*d.*) is a collection of "four essays with an introductory survey" by one of the leaders of modern research. *The Physical Principles of the Quantum Theory* by Heisenberg (C.U.P., 8*s.* 6*d.*) gives a mathematical analysis of the modern theory. *The Quantum Theory* by Temple (Methuen, 3*s.*) and *Electron Diffraction* by Beeching (Methuen, 3*s.*) are two specialist monographs covering the respective fields indicated by the titles.

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